Roadmap at the LHC to the Higgs Boson and Beyond

The plan:

Short history of the LHC
The experiments
Testing/Commissioning the detectors
Comments on computing
The physics landscape
Some physics results
- ***Standard Model***
- ***Higgs***
- ***Beyond the SM searches***

Outlook

(Note that I will use often examples from ATLAS, but the ~same applies for CMS!

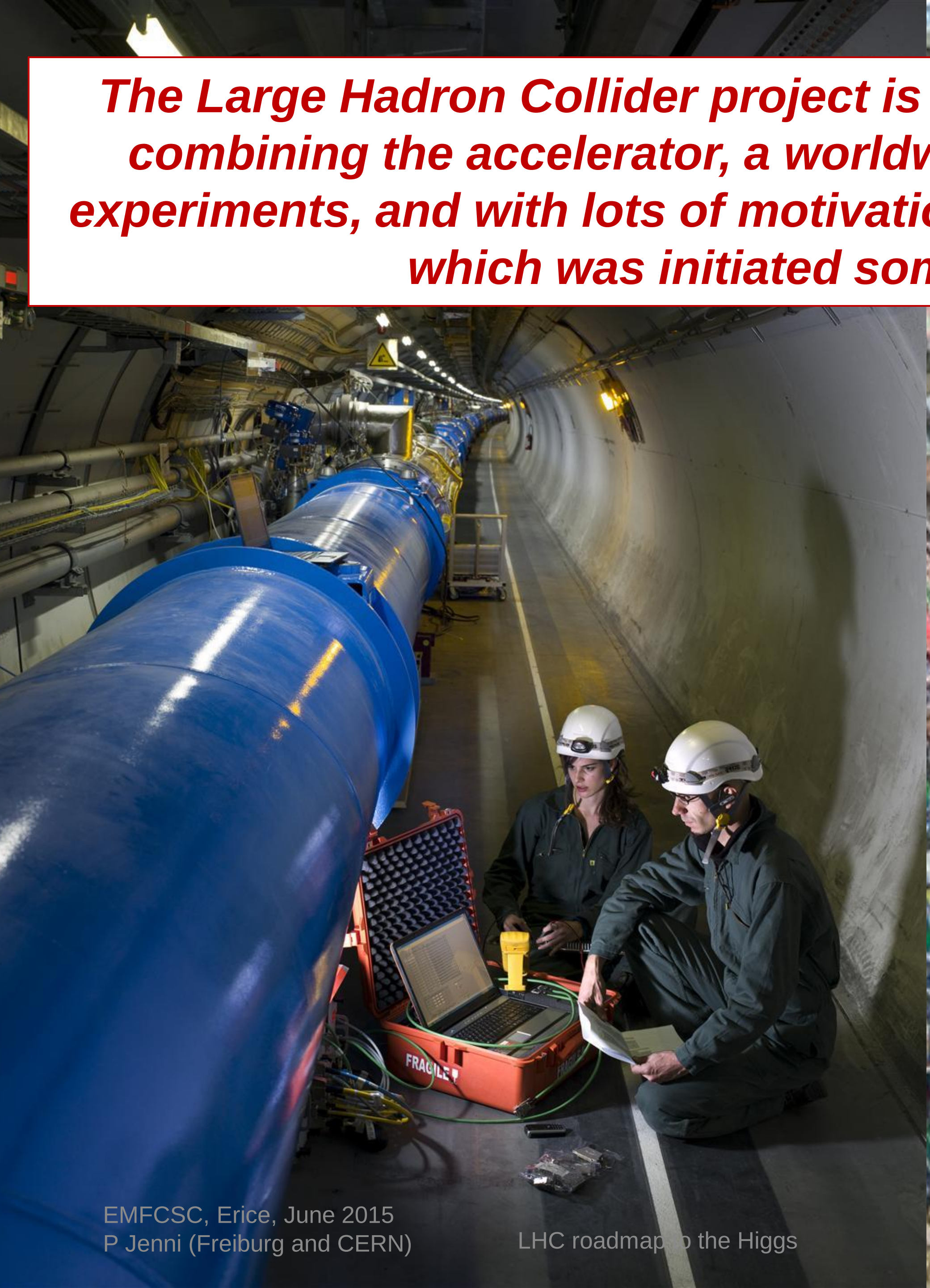
Also, the emphasis is sometimes not on the most up-to-date plots, rather on best illustrations to make a given point)

53rd Ettore Majorana International School of Subnuclear Physics
EMFCSC, Erice, 24 June – 3 July 2015

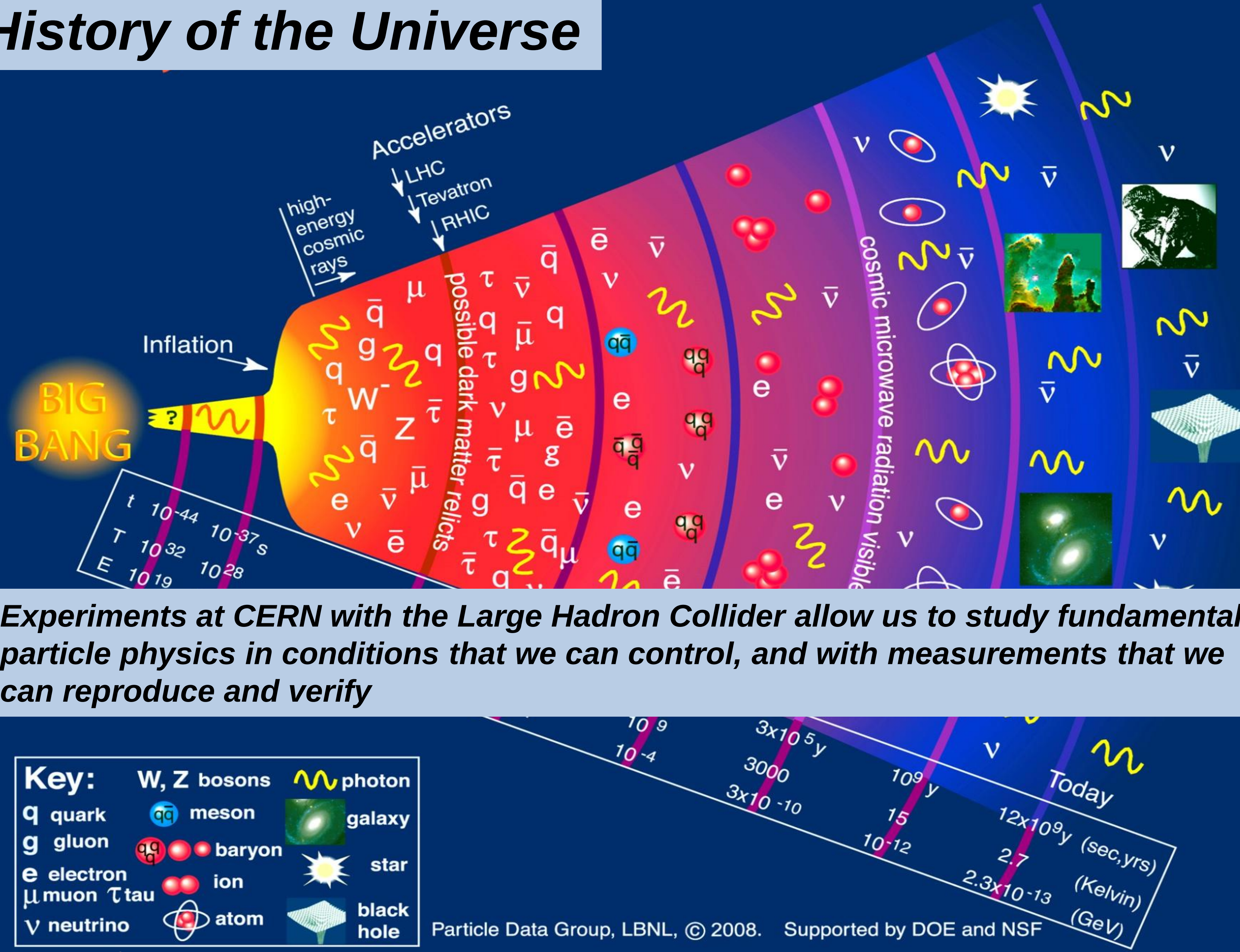
Drawing by Sergio Cittolin

Peter Jenni, Freiburg and CERN

The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, and with lots of motivation from our theory colleagues, which was initiated some 30 years ago

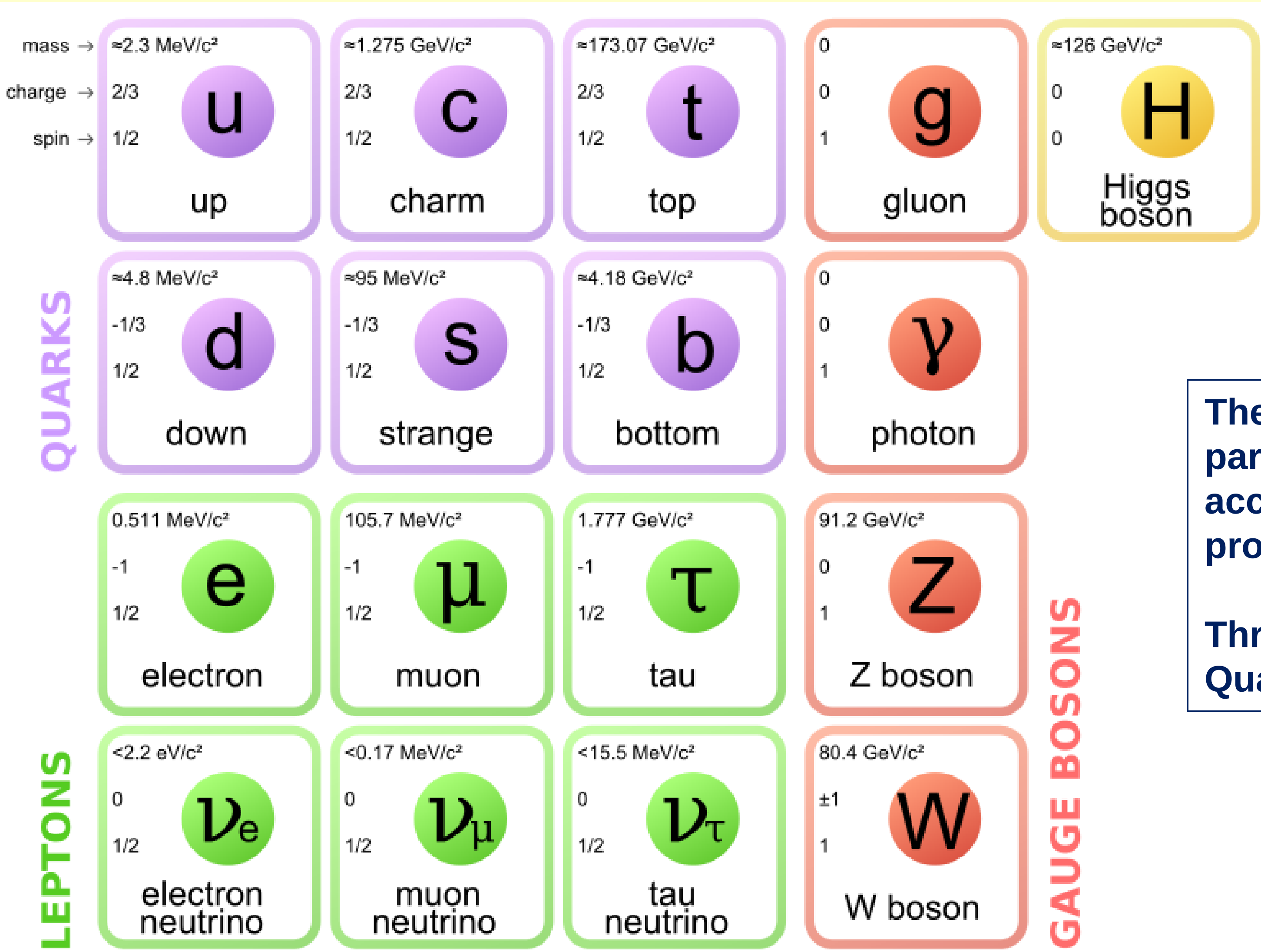


History of the Universe



Experiments at CERN with the Large Hadron Collider allow us to study fundamental particle physics in conditions that we can control, and with measurements that we can reproduce and verify

Standard Model of Elementary Particles



← ***Fermions*** → ← ***Bosons*** →

The elementary particles arranged according to their properties

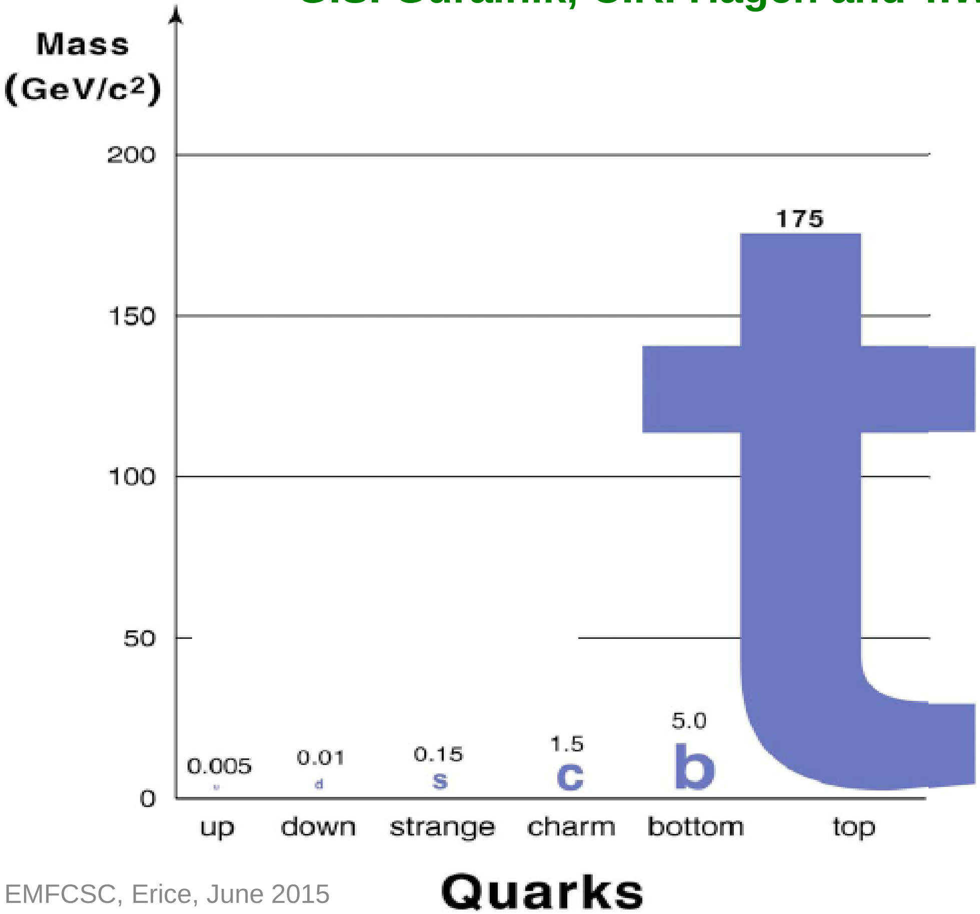
Three families of Quarks and leptons

A most basic question is why particles (and matter) have masses (and so different masses)

The mass mystery for fundamental particles could be solved with the 'EW symmetry breaking mechanism' which predicts the existence of a new elementary particle, the 'Higgs' particle (theory 1964: R. Brout and F. Englert; P.W. Higgs; G.S. Guralnik, C.R. Hagen and T.W.B. Kibble)

Peter Higgs

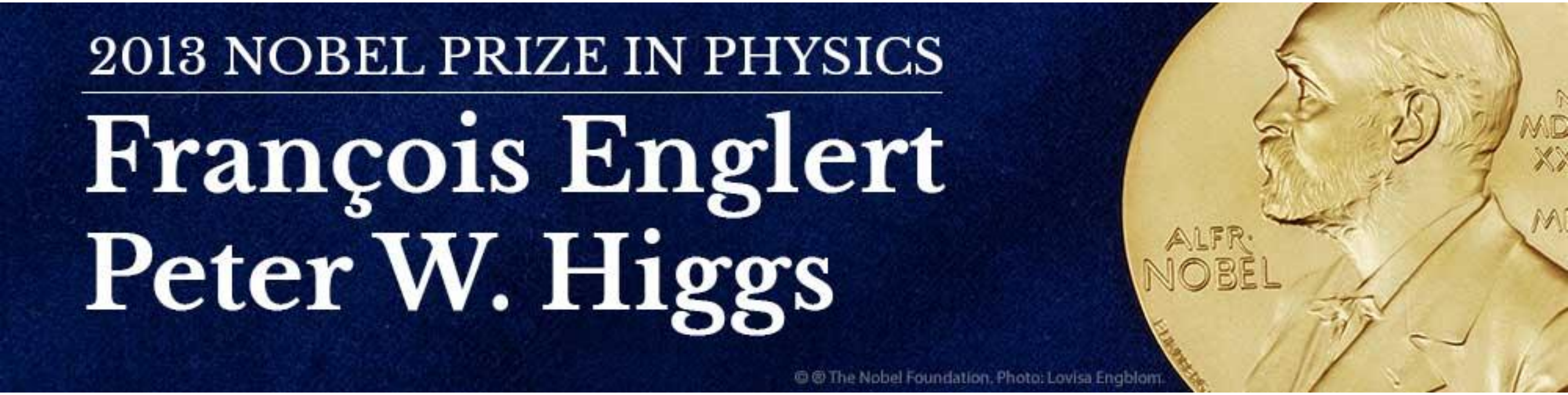
The Higgs (H) particle has been searched for since decades at accelerators … motivated LHC

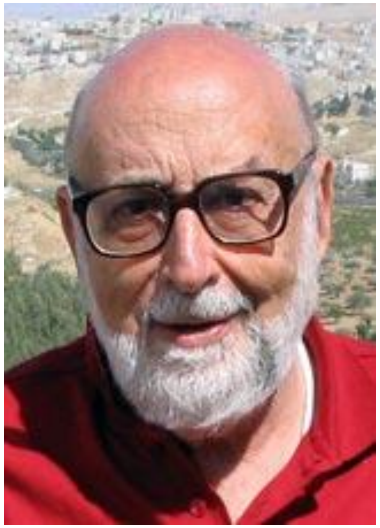


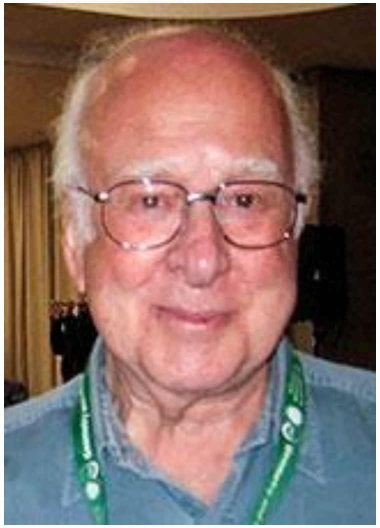
Robert Brout (1928-2011)

Francois Englert

Announced on 8th October and celebrated on 10th December 2013:







"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

How the LHC came to be …

(see a nice article by Chris Llewellyn Smith in Nature 448, p281)

Some early key dates

1977 The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future

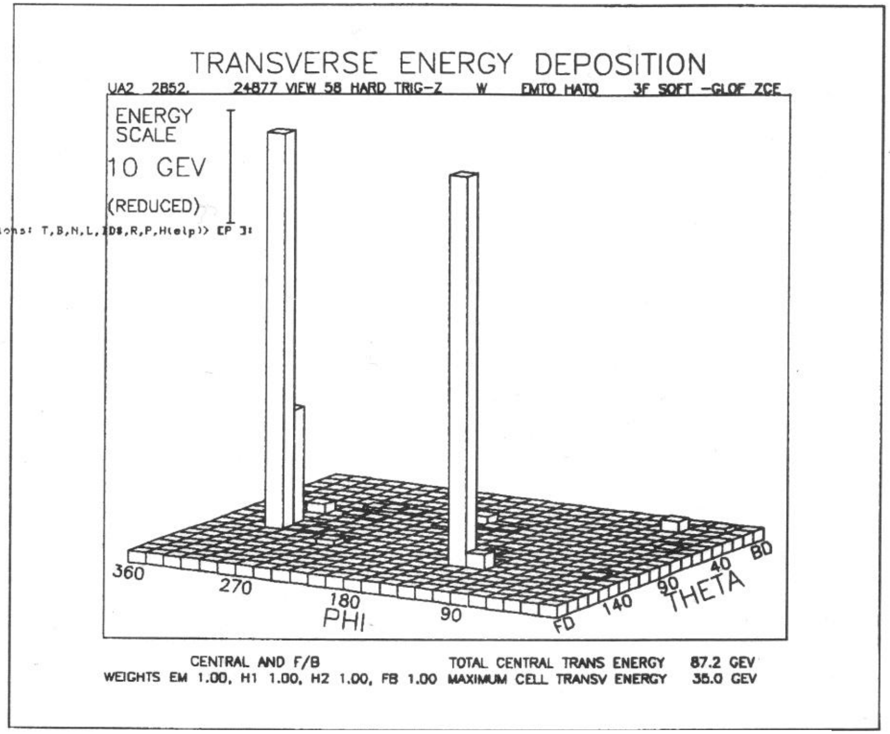
1981 LEP was approved with a large and long (27 km) tunnel

1983 The early 1980s were crucial:

The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

This also triggered a famous quote from a 1983 New York Times editorial:

'Europe: 3 - US Not Even Z-Zero'



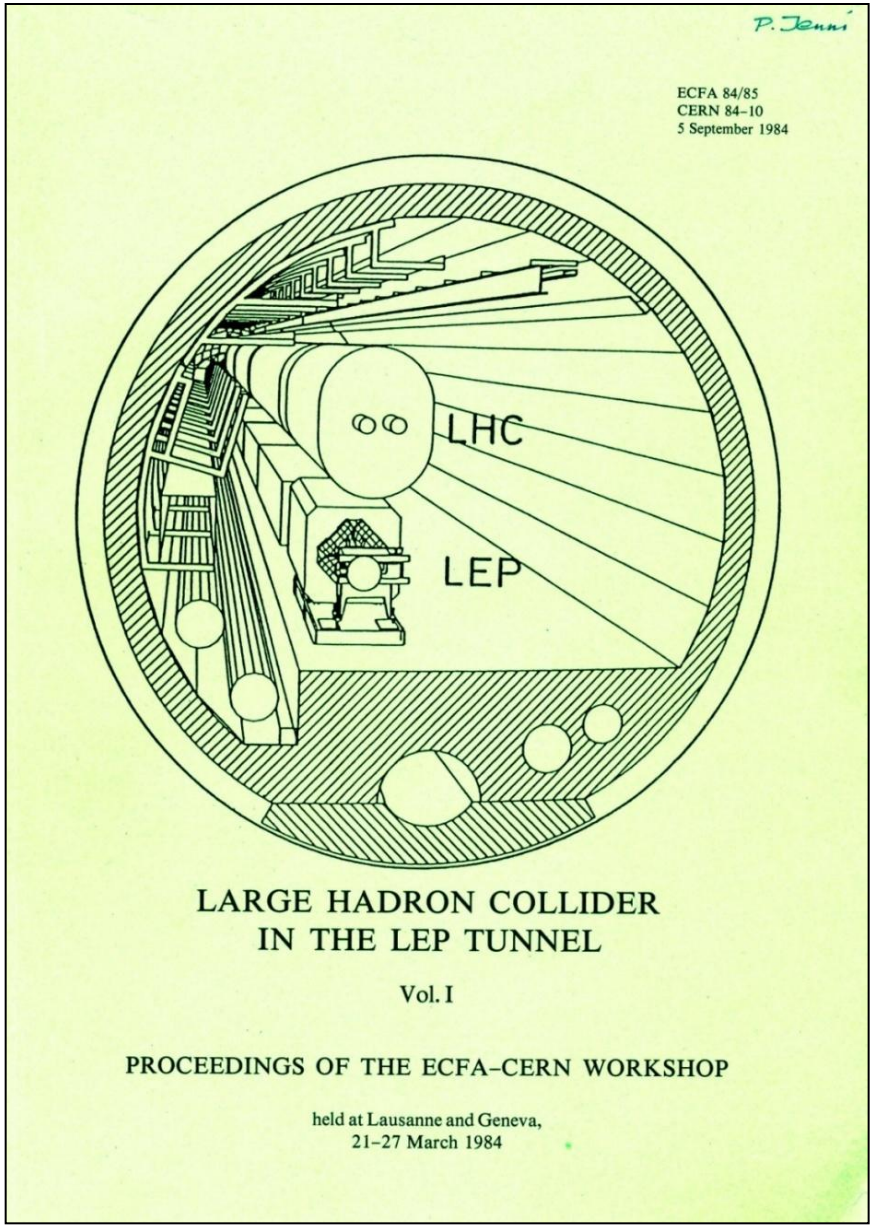
A very early Z → ee online display from one of the detectors (UA2)

1984 For the community it all started with the CERN - ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

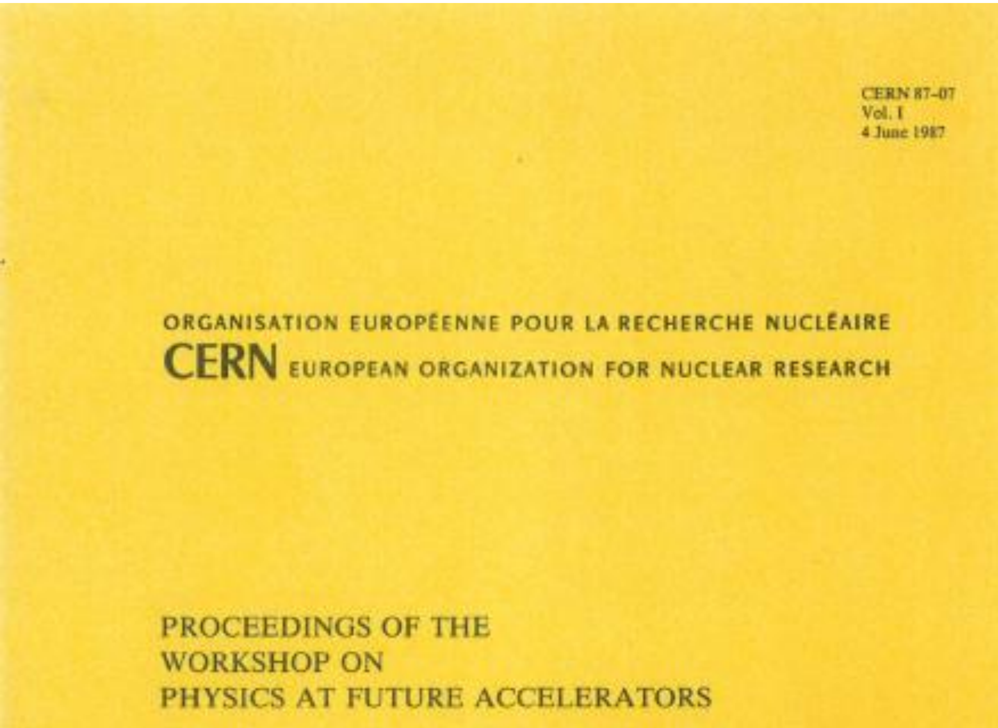
1986 LAA R&D on new detector technologies started, later followed by the DRDC

1987 La Thuile Workshop

Many LHC colleagues were already involved in this WS set up by Carlo Rubbia as part of the Long Range Planning Committee



Some history: 28 years ago …
La Thuile 7 – 13 January 1987
(Carlo Rubbia's Long Range Planning Committee)



CERN 87-07
Vol. I
4 June 1987

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

La Thuile (Italy) and Geneva (Switzerland)
7 - 13 January 1987

Vol. I

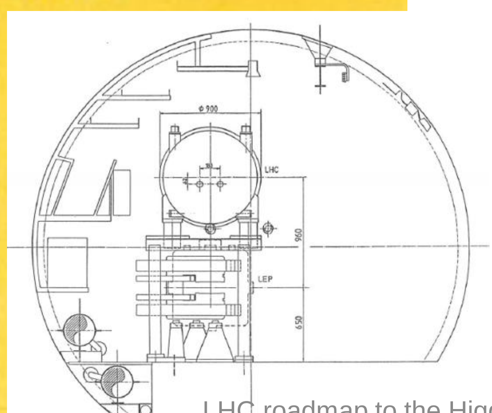
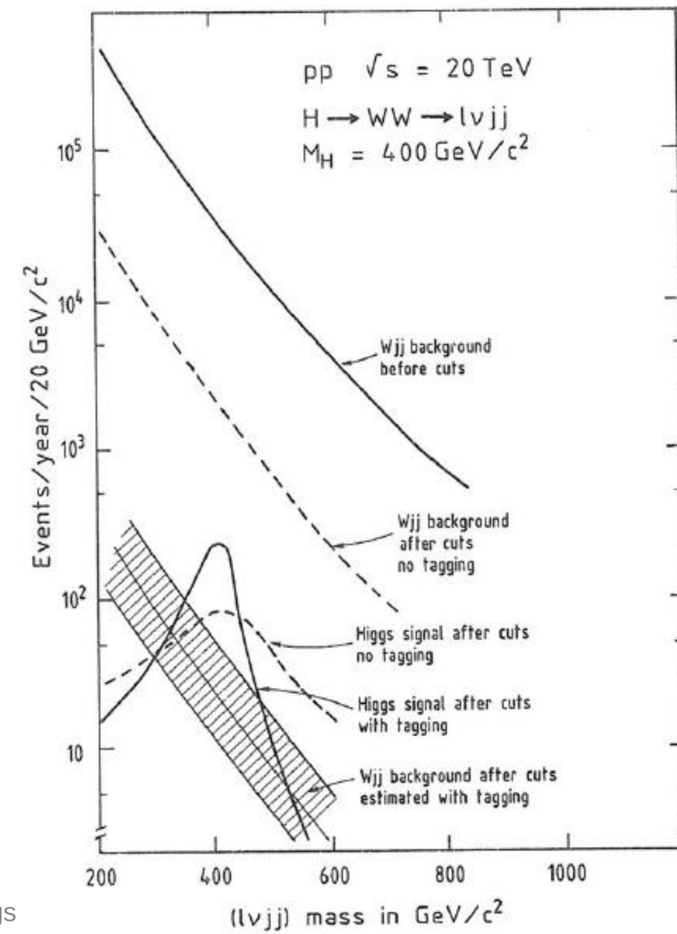


Fig. 1

Collider parameters

Machine		$\sqrt{s}$ (TeV)	L ($cm^{-2}s^{-1}$)
LHC	pp	16	$10^{33} \rightarrow 10^{34}$
	ep	1.3	10^{32}
		1.8	10^{31}
CLIC	e^+e^-	2	$10^{33} \rightarrow 10^{34}$



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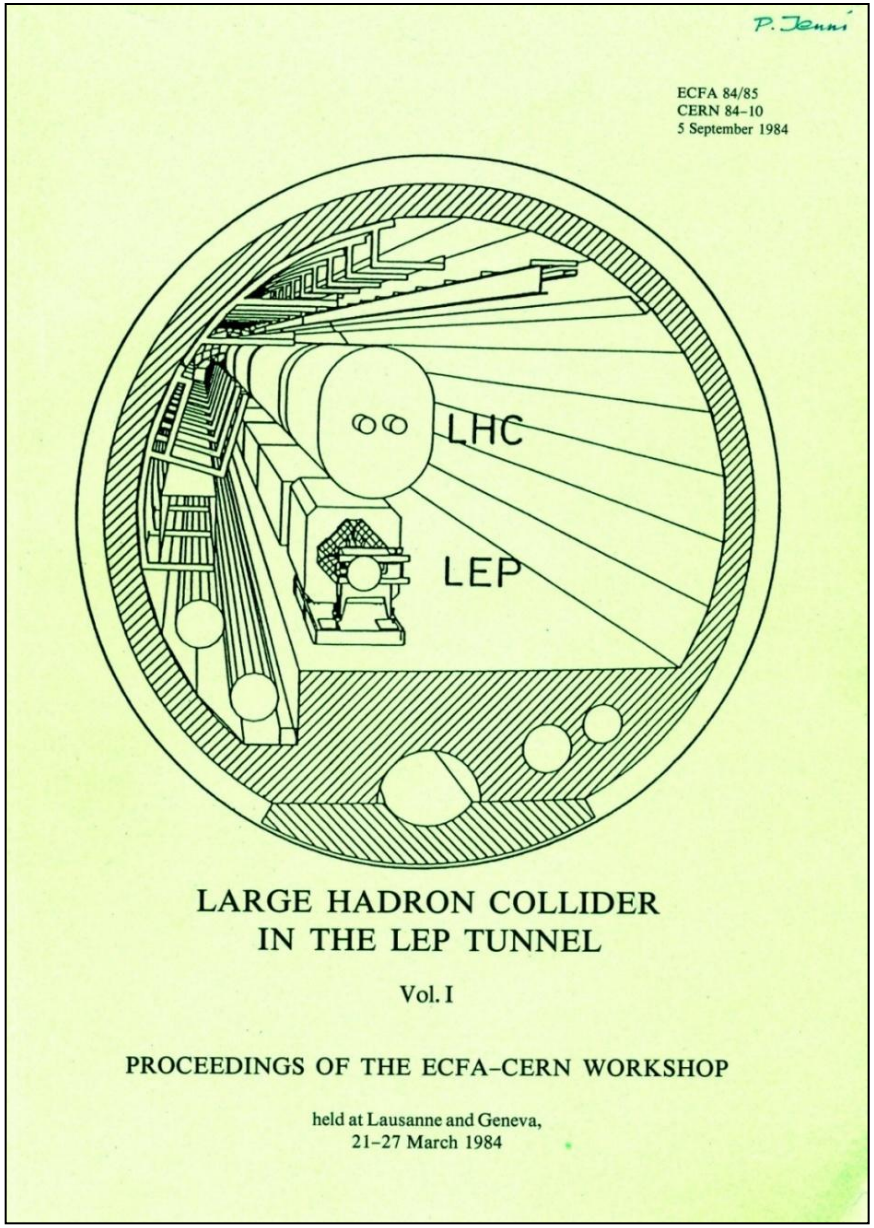
1989 ECFA Study Week in Barcelona for LHC instrumentation

1990 Large Hadron Collider Workshop Aachen (CERN - ECFA)

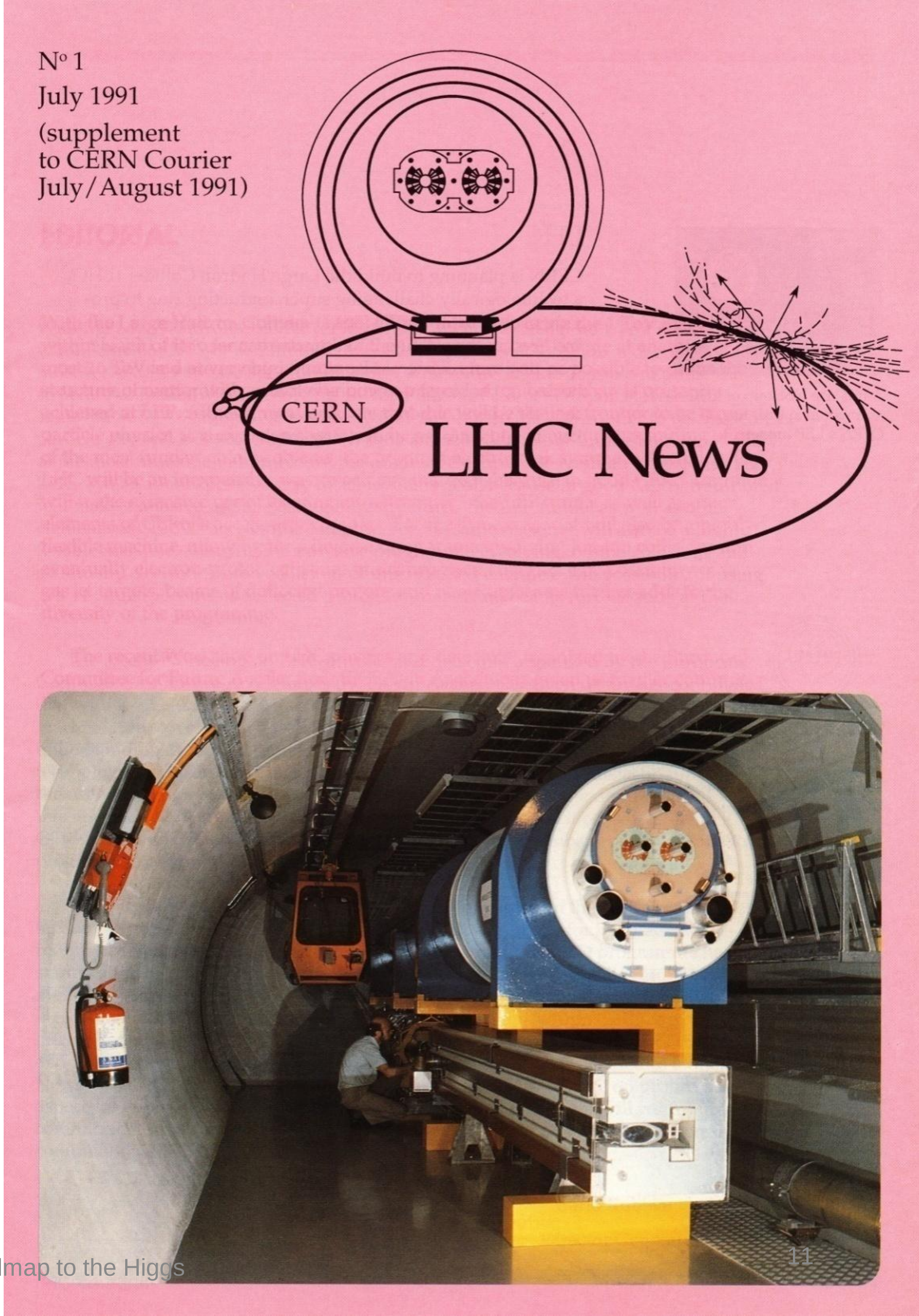
1992 CERN – ECFA meeting 'Towards the LHC Experimental Programme' in Evian

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, more than 20 years ago



1991 December CERN Council: 'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002


Nº 1
July 1991
(supplement
to CERN Courier
July/August 1991)

CERN
LHC News

1994 In order to have any chance at all of approval, the idea of a staged construction was worked out by the then new CERN DG Chris Llewellyn-Smith

ATLAS provided comparisons between 10 and 14 TeV…
→ worthwhile to start with

June 1994 Council:

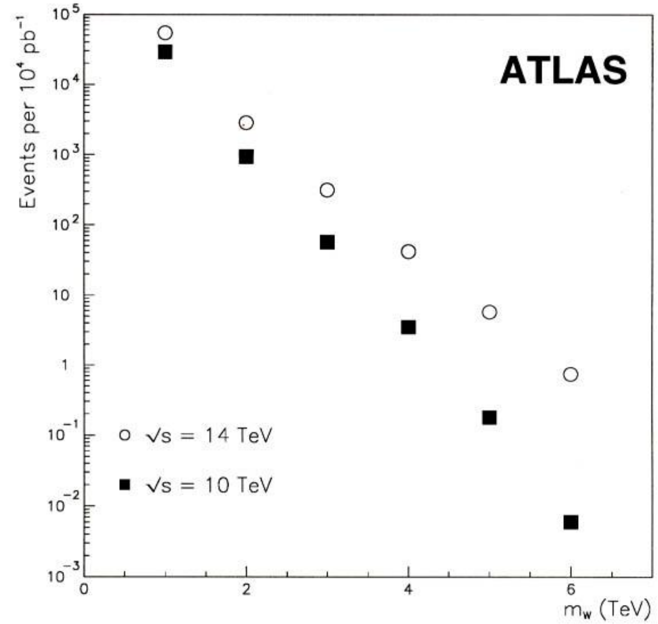
Staged construction was proposed, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

Two-stage construction of LHC was approved

Search for new, heavy, gauge bosons

Number of W' decays into $e\nu$ or $\mu\nu$ for 10^4 pb^{-1}



The accessible mass range is affected by both the lower energy and luminosity

The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, India, Canada and the USA were agreeing in that phase to contribute to the LHC

(Israel contributed all along to the full CERN programme and LHC before it became finally a Member State on 6th January 2014)

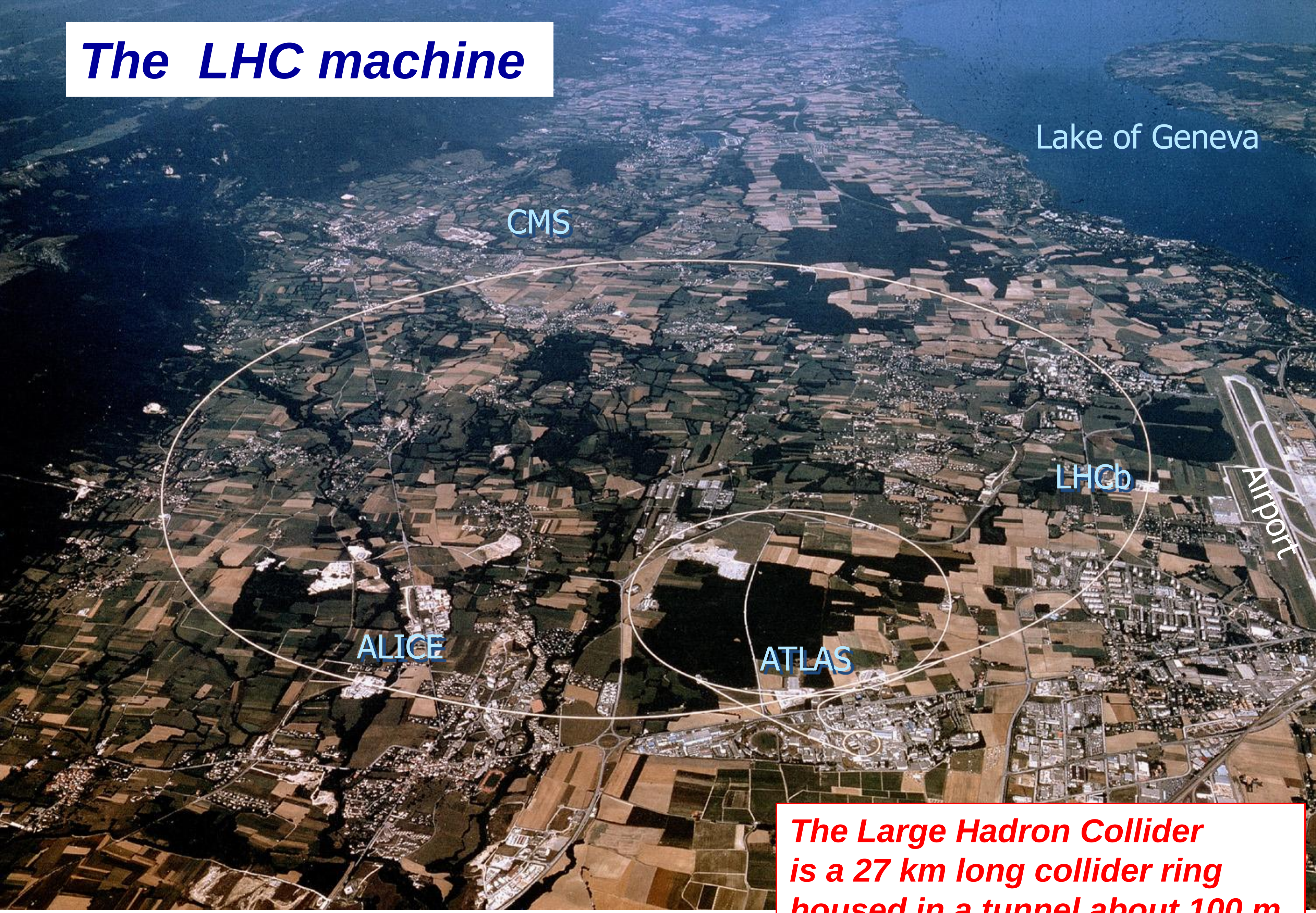
1996

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with L Maiani and A Skrinsky in the centre

The first picture on the Web in 1992 !

The LHC machine

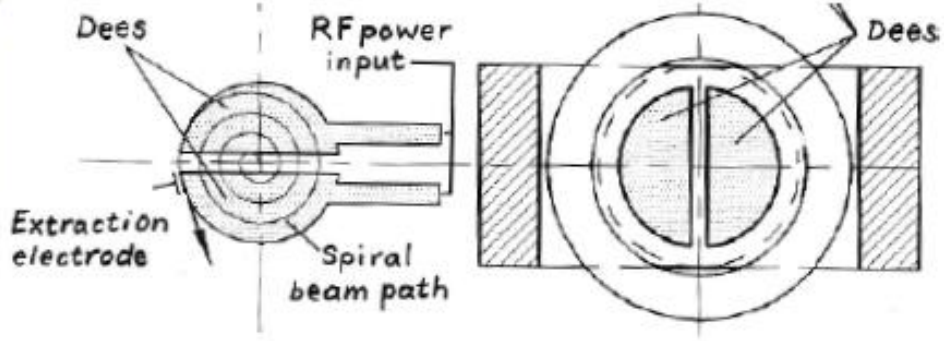


The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

The first cyclotron, and the famous 184” one of Berkeley

Ernest Lawrence
(1901 - 1958)

184” 1946



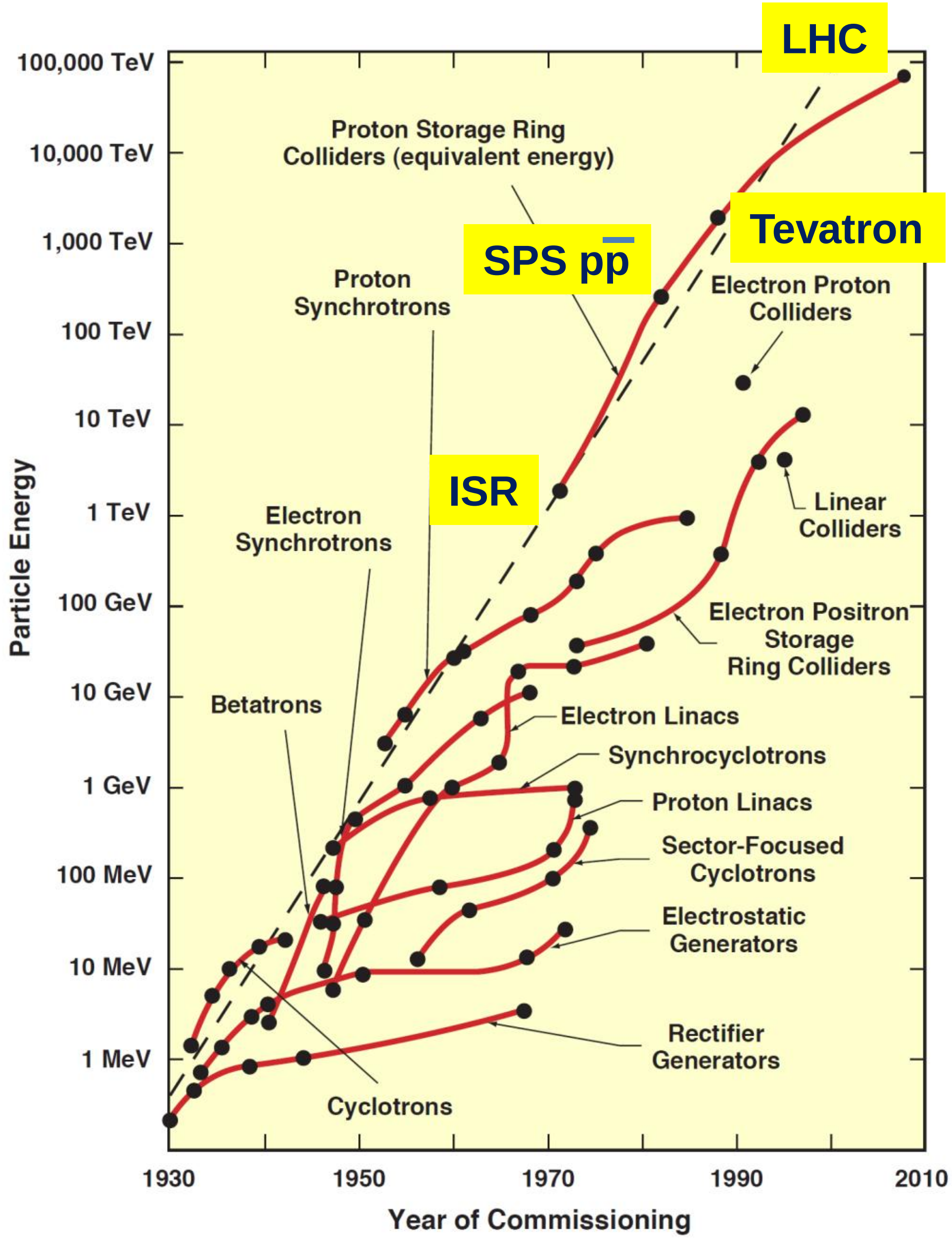
The first circular accelerator (Berkeley 1930)

The history of accelerators

An exponential development over 70 years,

following emerging technologies,

superconductivity has been the key technology for high energy accelerators since the 1980's.

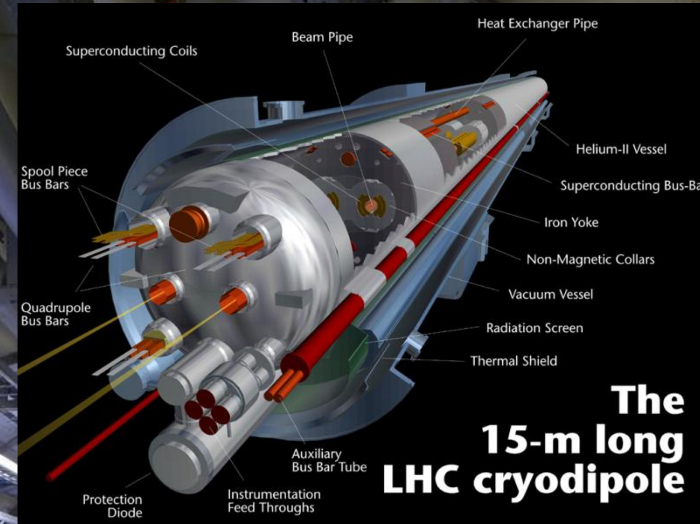


Livingston chart

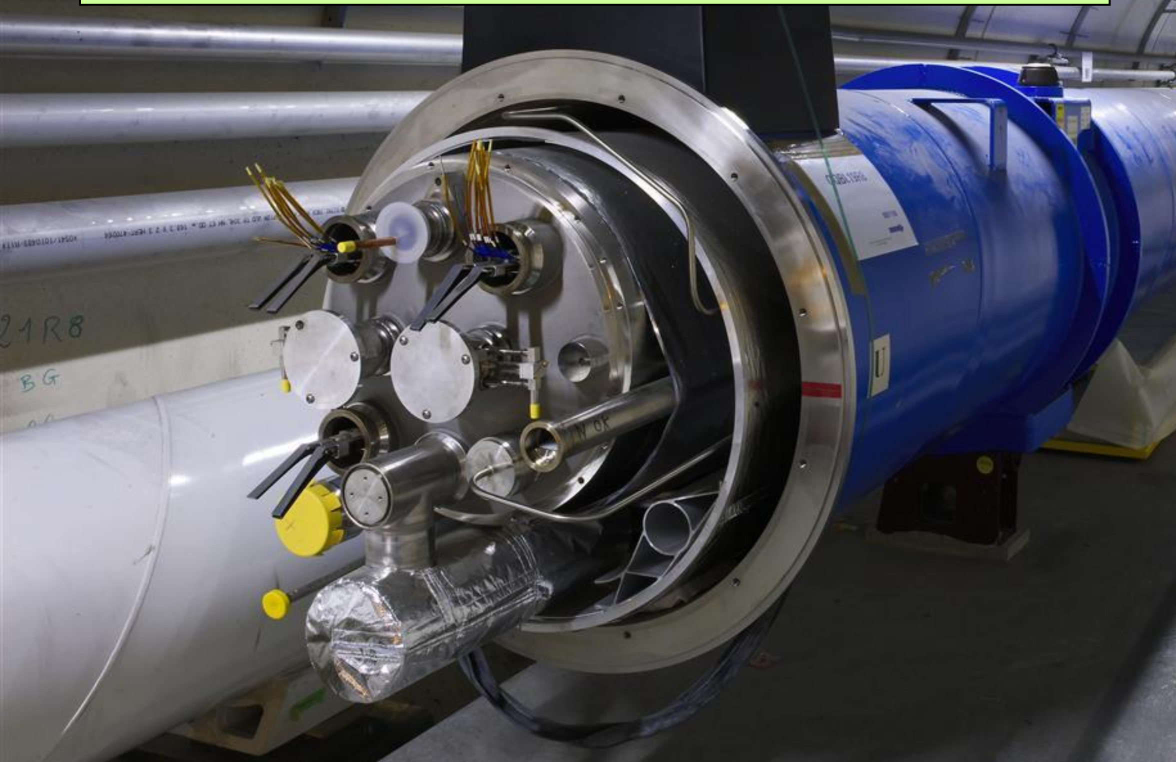
The most challenging components were the 1232 high-tech superconducting dipole magnets

Magnetic field:	**8.4 T**
Operation temperature:	**1.9 K**
(120 tons of superfluid Helium)	
Dipole current:	**11700 A**
Stored energy:	**7 MJ**
Dipole weight:	**34 tons**

7600 km of Nb-Ti superconducting cable

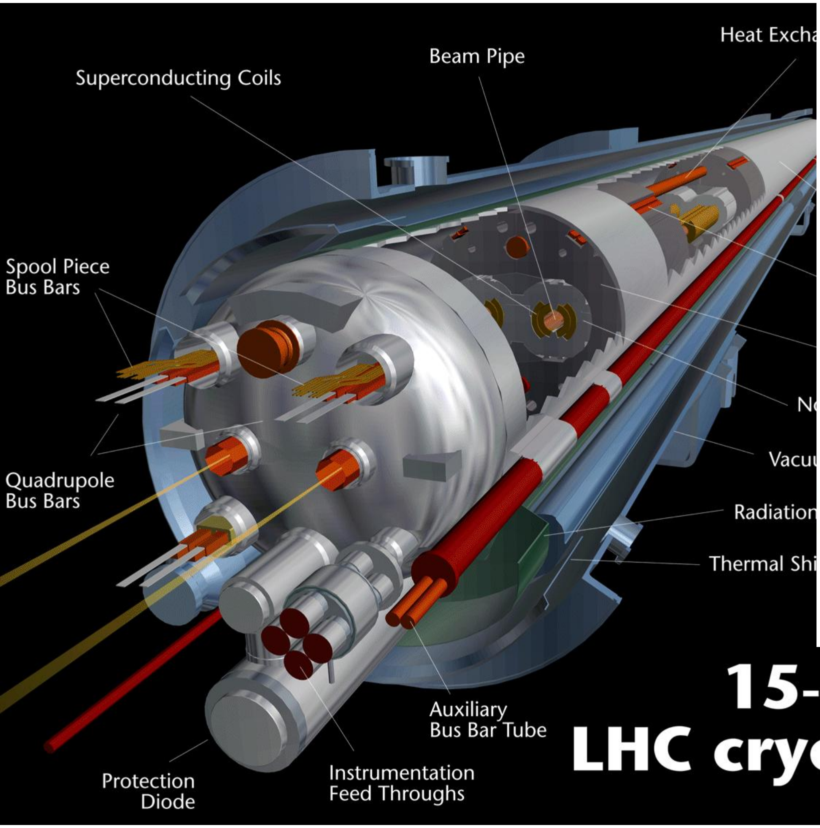


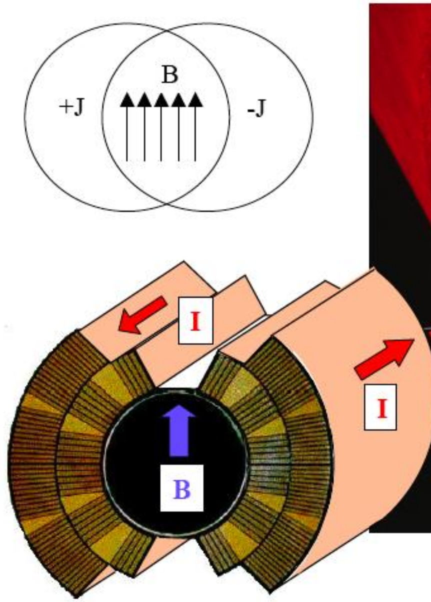
p(TeV) = 0.3 B(T) R(km)

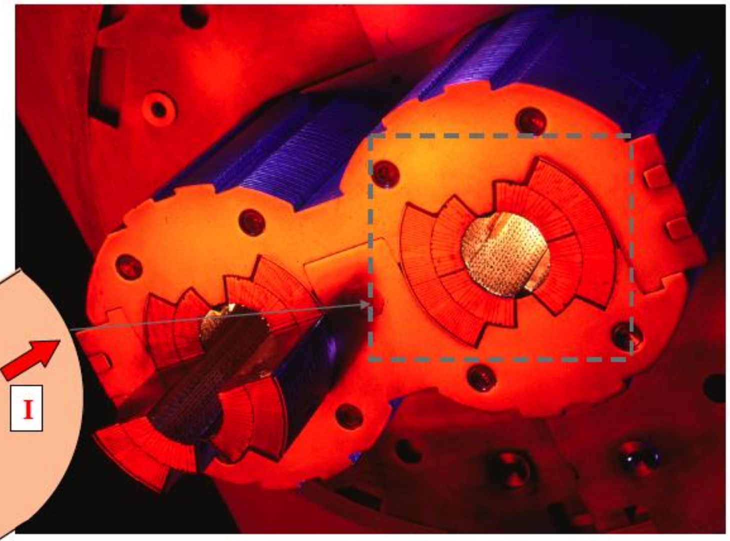


LHC Construction Project Leader Lyndon Evans

LHC Accelerator Challenge: Dipole Magnets







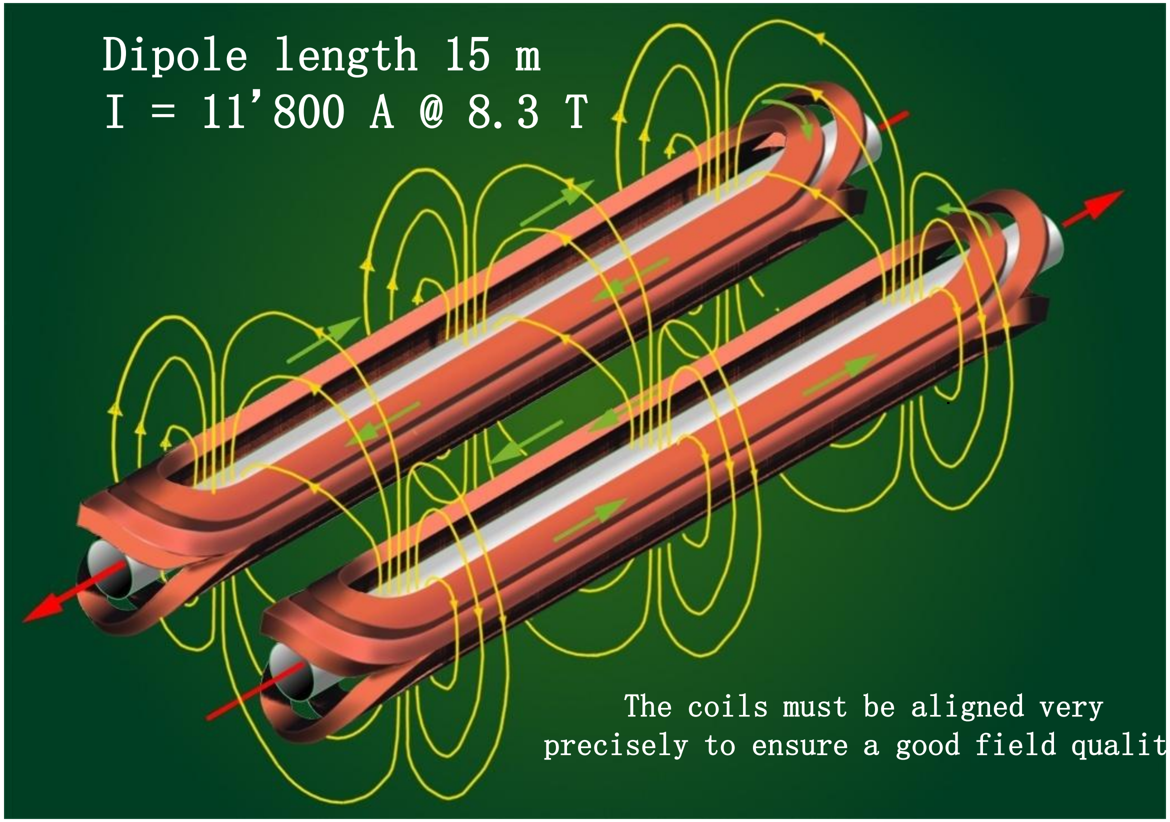
Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

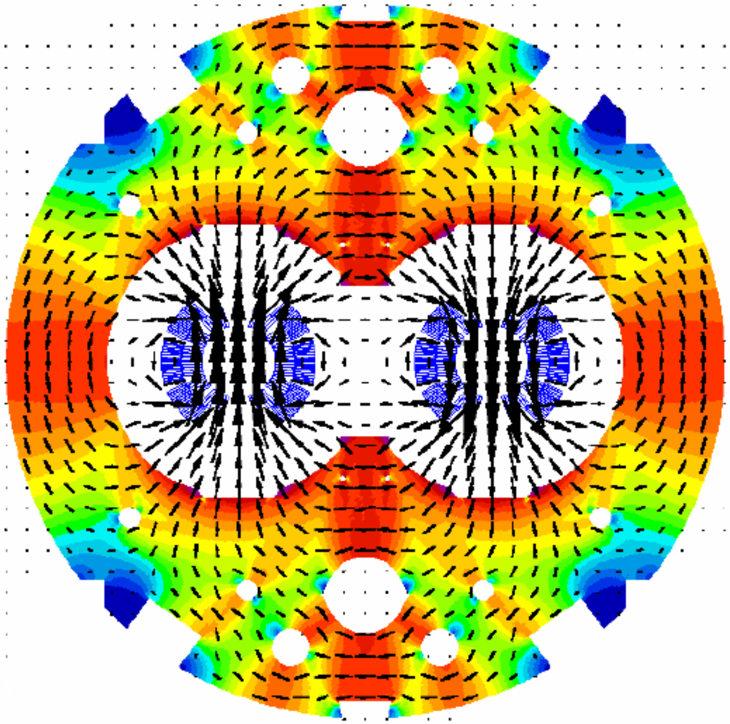
For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

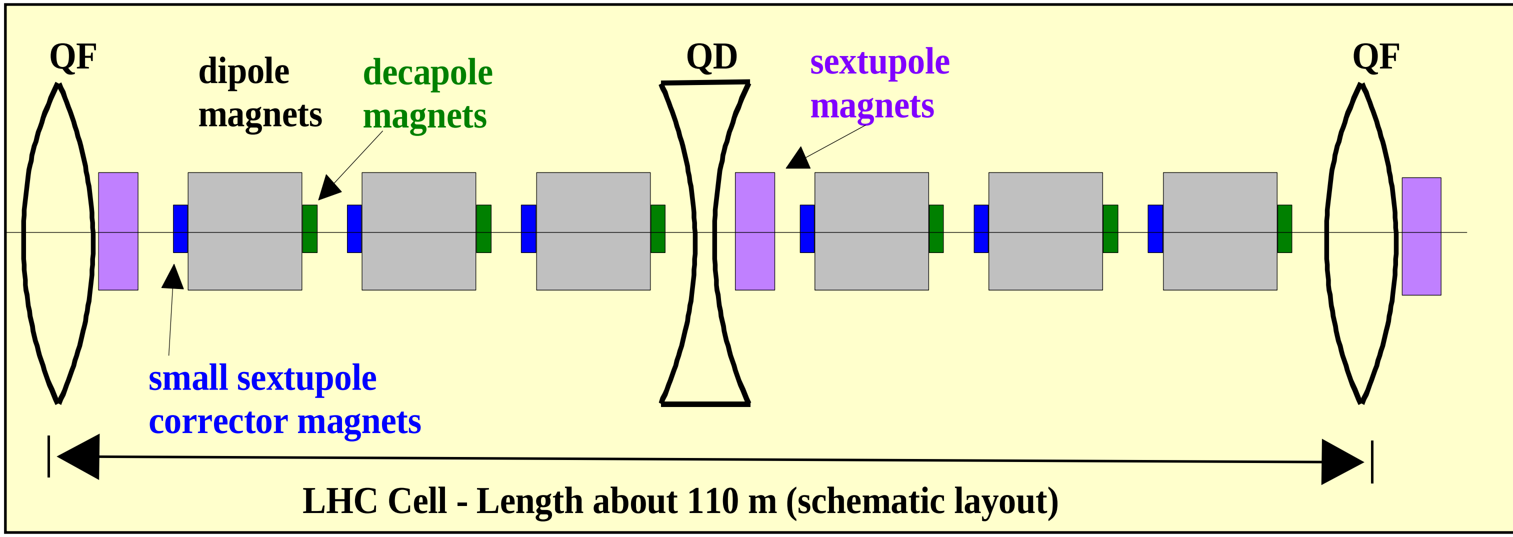
LHC magnets are cooled with pressurized superfluid helium

Coils in the LHC dipoles





Beam transport (LHC arcs)



Dipole- and Quadrupole magnets

- Particle trajectory stable for particles with nominal momentum

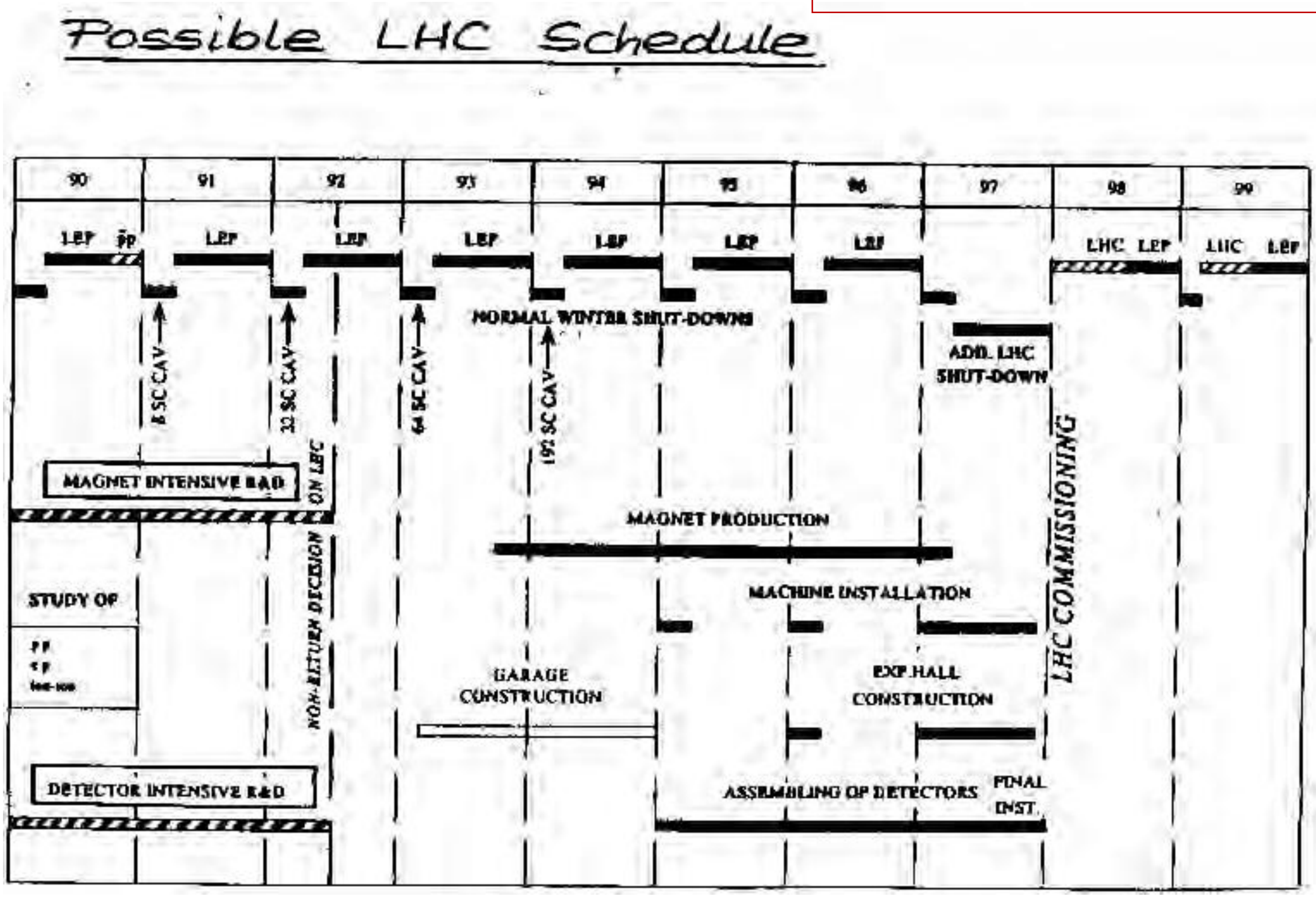
Sextupole magnets

- To correct the trajectories for off-momentum particles
- Particle trajectories stable for small amplitudes (about 10 mm)

Multipole-corrector magnets

- Sextupole - and decapole corrector magnets at end of dipoles
- Particle trajectories can become unstable after many turns (even after 10^6 turns)

From a very early talk about the LHC, must have been around 1987 …



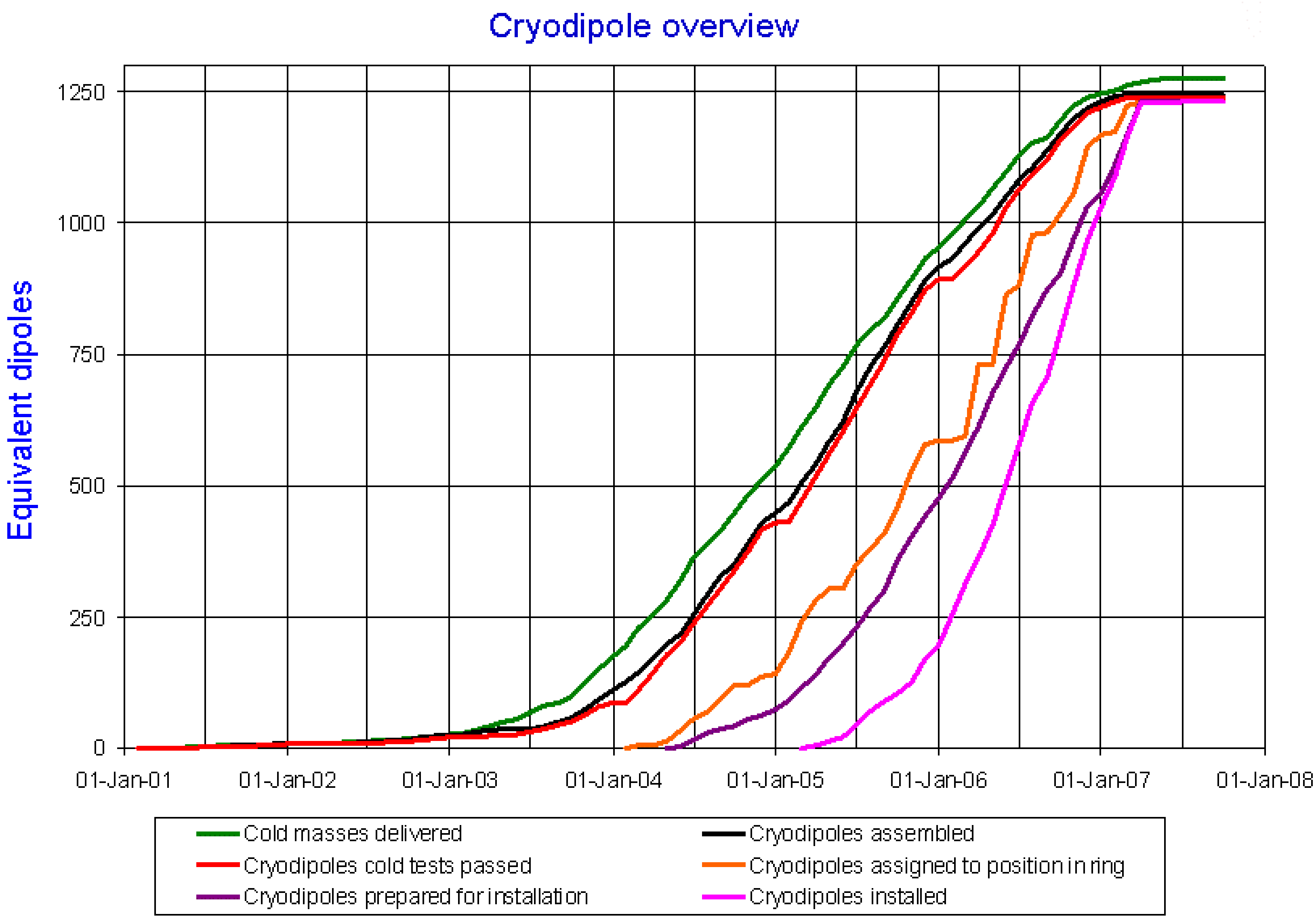
Descent of the last dipole magnet, 26 April 2007

30’000 km underground transports at a speed of 2 km/h!

LHC Progress Dashboard

History of the dipole magnet construction and installation

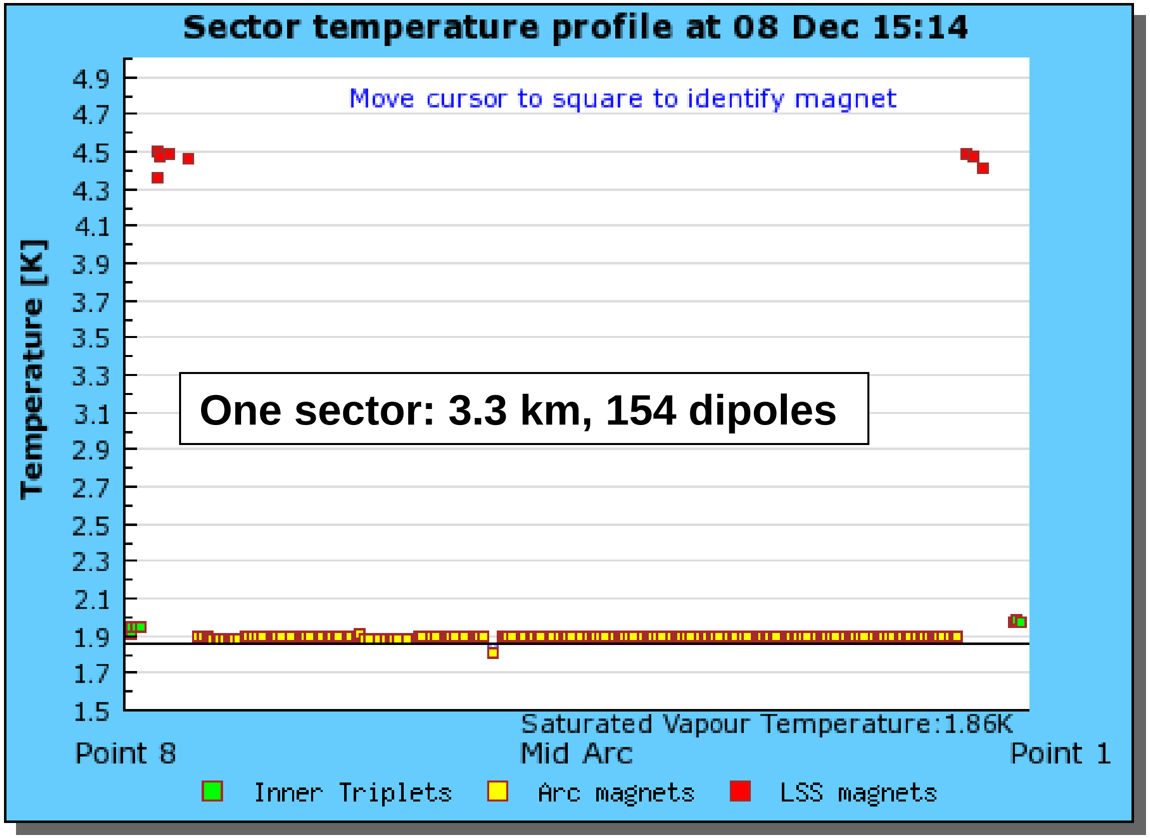
Accelerator Technology Department



Updated 30 September 2007

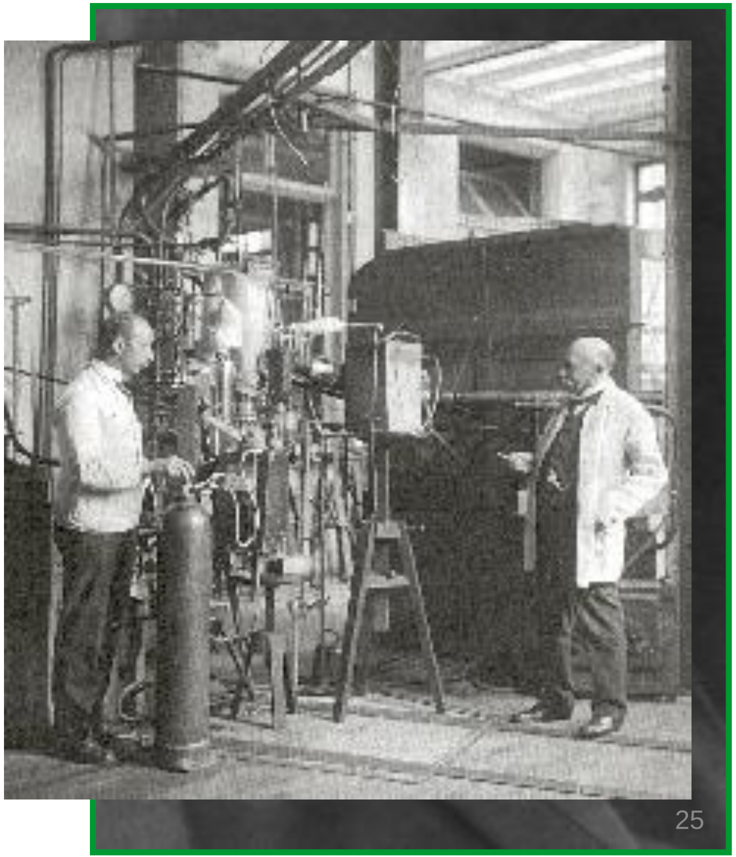
Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

The LHC is the largest cryogenic system on earth, cooler than outer space



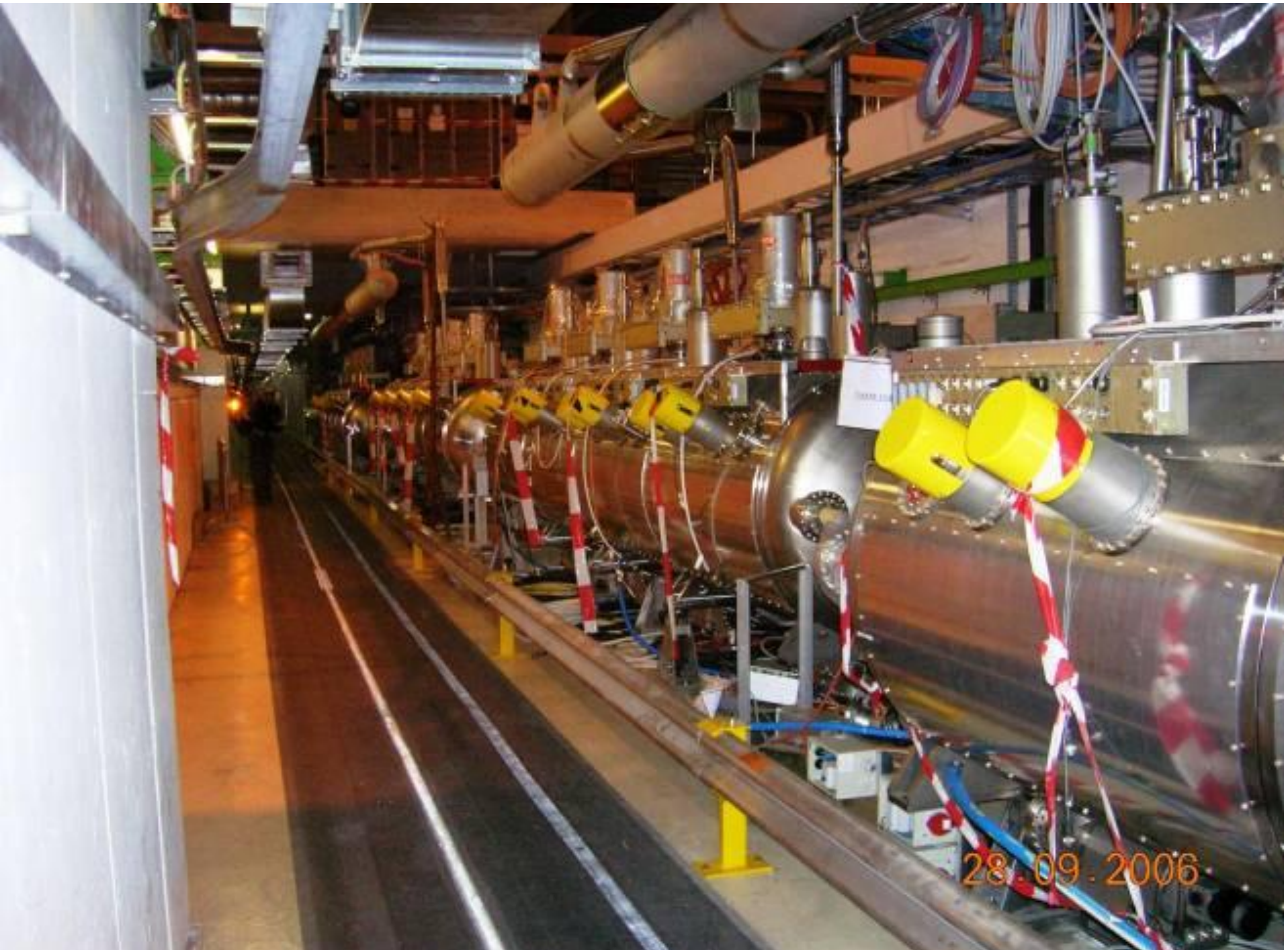
Magnets cooled down in a bath of ~120 tons of superfluid Helium (excellent thermal conductor)

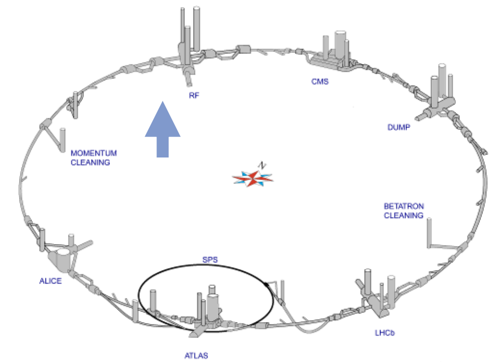
H K Onnes
Nobel Prize in Physics 1913



- **107 years ago, on 10 July 1908: Heike K Onnes first liquefied Helium (60 ml in 1 hour) in Leiden**
- **LHC today: 32000 He liters liquefied per hour by eight big cryogenic plants (the largest refrigerator in the world)**

The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities

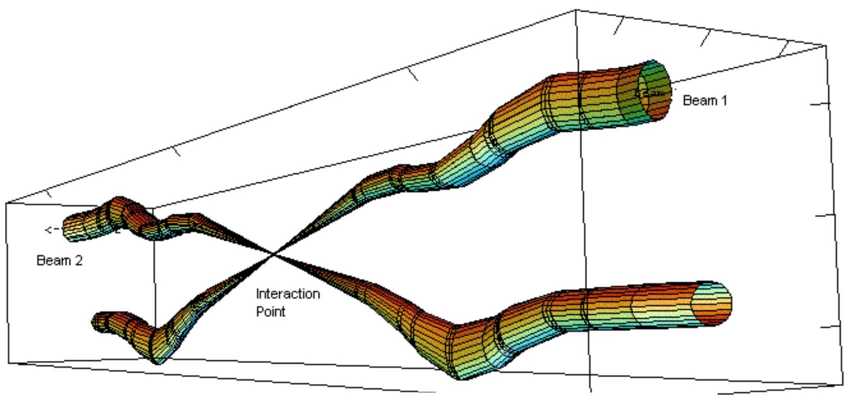




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

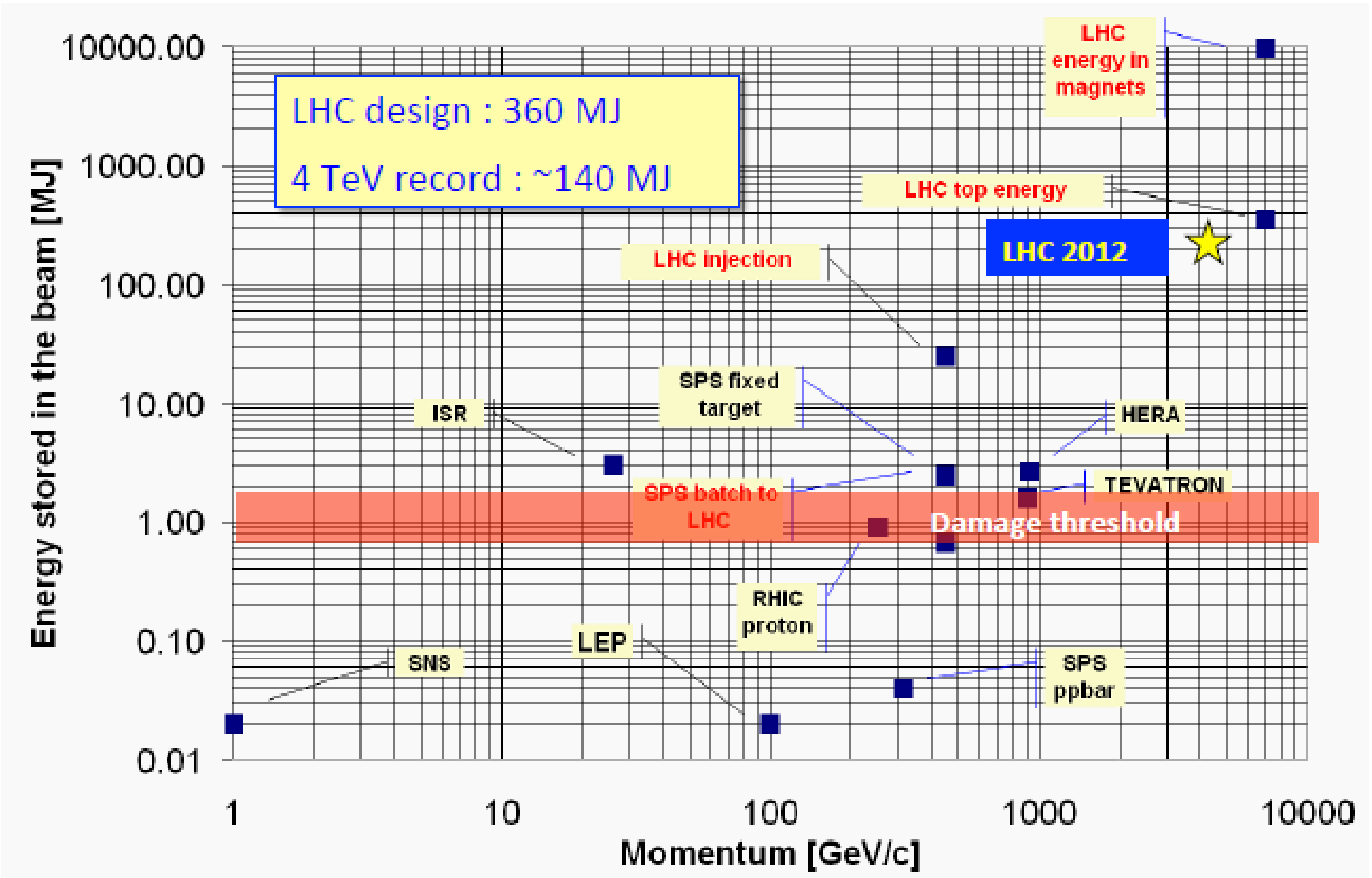
Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments



Relative beam sizes around the collision point

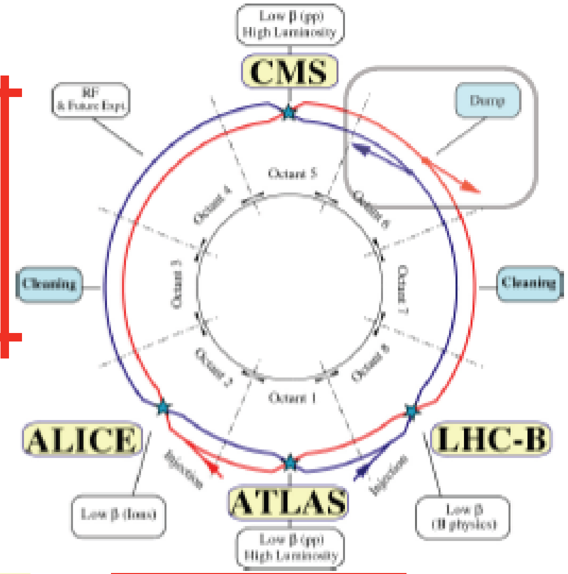
Stored Energy

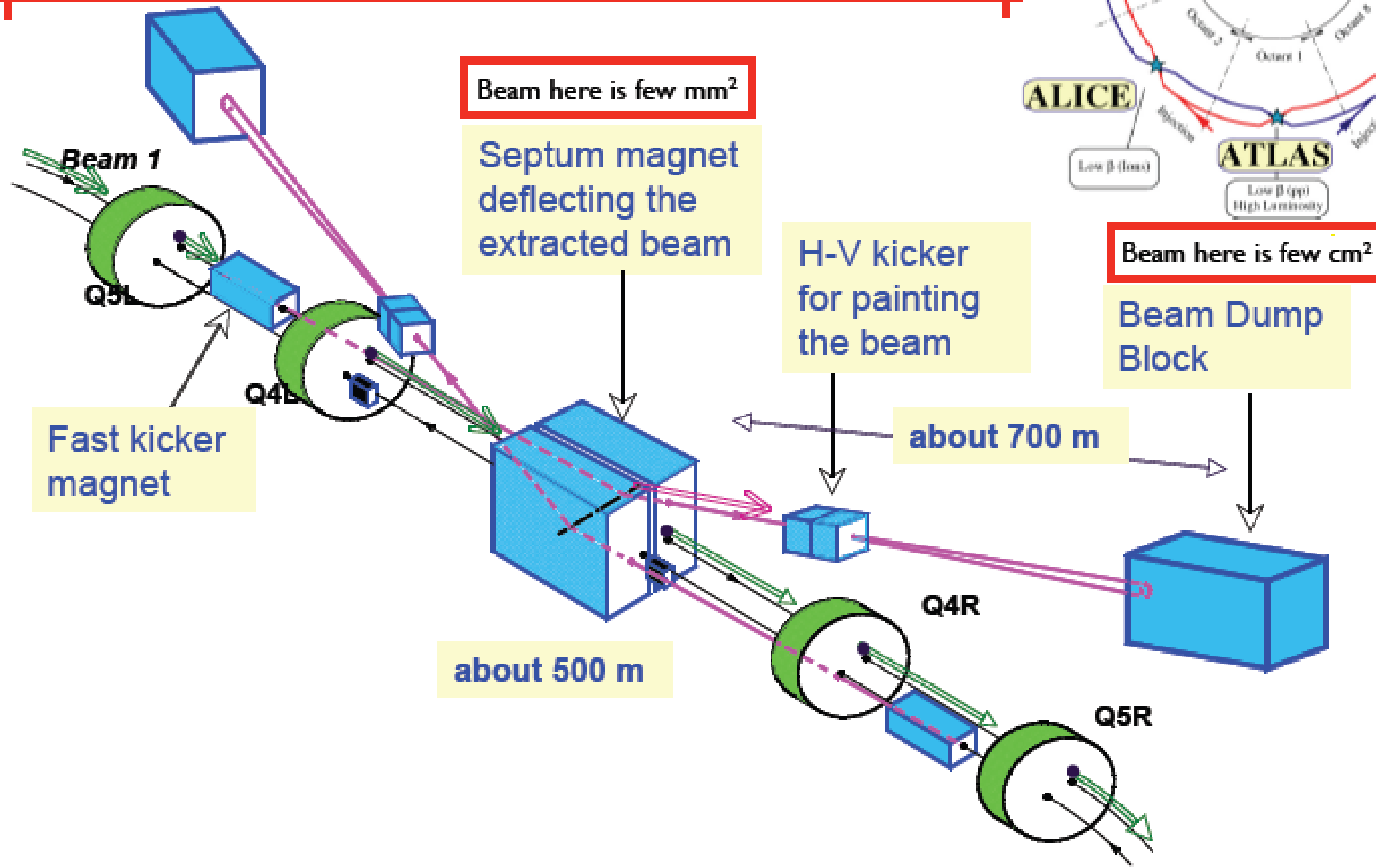
The stored energy in beam and magnets is orders of magnitude above damage threshold: LHC key system ➔ Machine Protection System



Beam extraction, emergency or not...

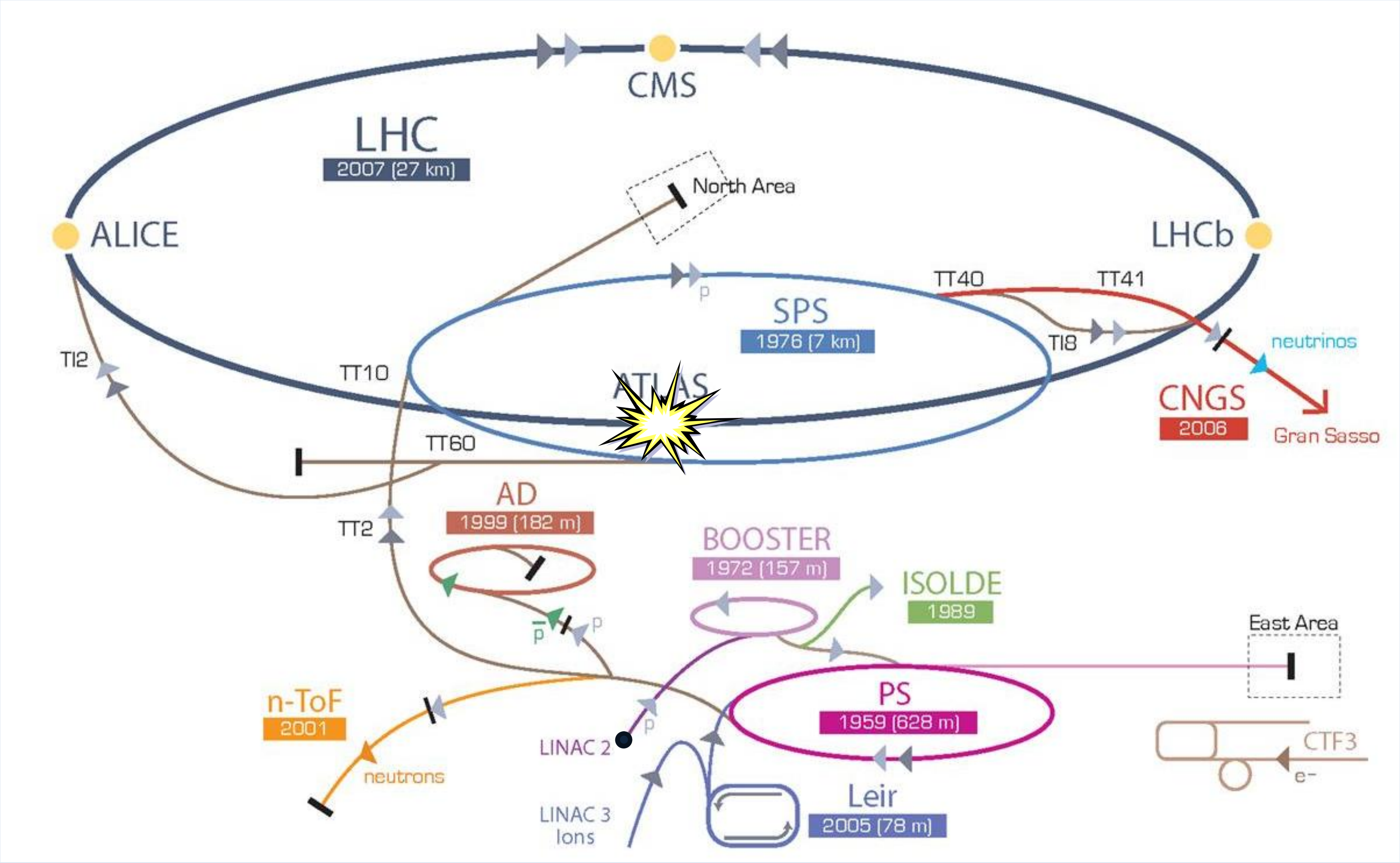
At the end of every "fill", when too low luminosity, or when BLM system triggers, both beams extracted on an external beam dump, in one turn.
Beam dump built to absorbe full power at full energy.



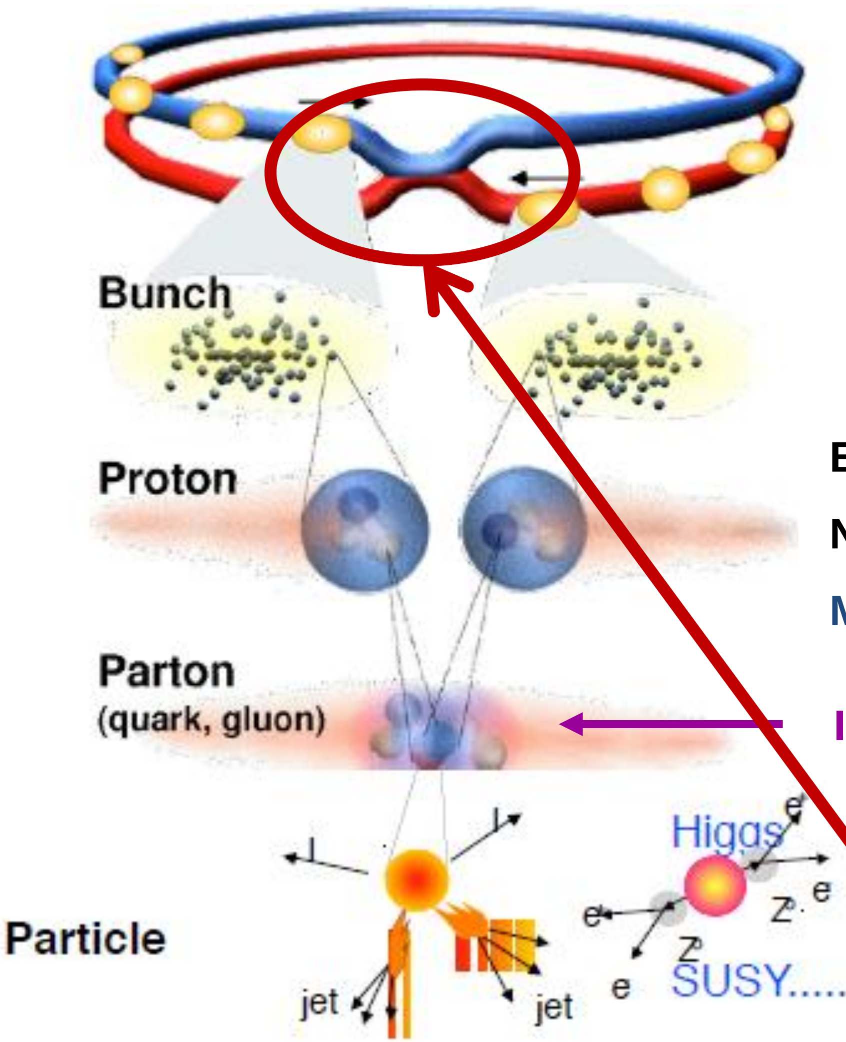


One of the two LHC beam dumps

LHC and CERN's particle accelerator chain



Collisions at the LHC



Proton - Proton	2808 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34}\,cm^{-2}s^{-1}$

Crossing rate 40 MHz

Event rate:

$N = L \times \sigma\,(pp) \approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

New physics rate ≈ .00001 Hz

Event selection:
1 in 10,000,000,000,000

→ Interesting events are very, very rare
→ One needs highly sophisticated instruments to find them

Arguing after the mid-1980s of being ambitious and design a general purpose detector …

A very simplified summary:

detector signature	accessible physics process
$\mu^\pm$	$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, $\not{p}_T$	add: $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ $W' \to \mu^\pm\nu$ compositeness $\tilde{q}, \tilde{g}$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, $\not{p}_T$ (non-)magnetic central part (<u>reduced</u> tracking)	add: 4× rate $H \to ZZ \to 4e^\pm$ 2× rate $H \to ZZ \to e^+e^-\nu\bar{\nu}$ 2× rate Z', W' $\tilde{q}, \tilde{g}$ (also cascade decays) mass resolution $e\mu$ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, $\not{p}_T$ full momentum and tracking	add: more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e <u>and</u> μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

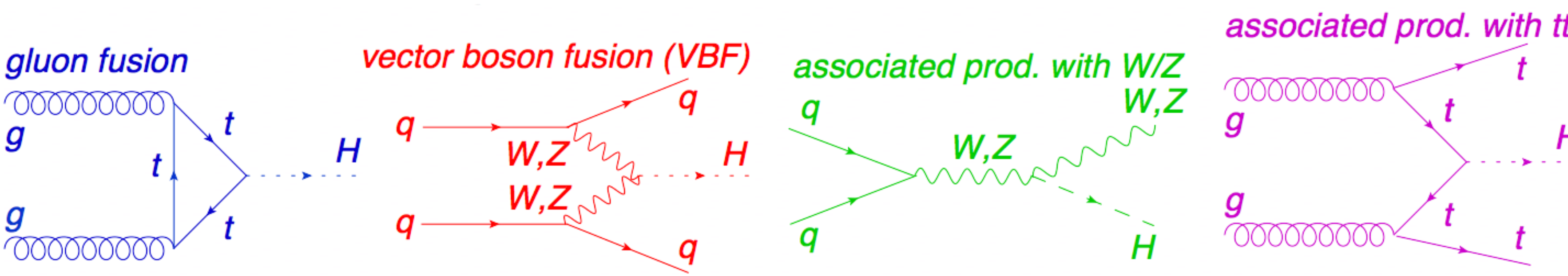
Electrons are relatively easy to measure but hard to identify at 10^{34}

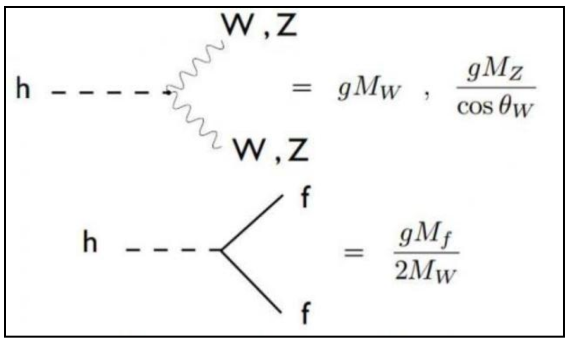
(radiation-hard inner detector)

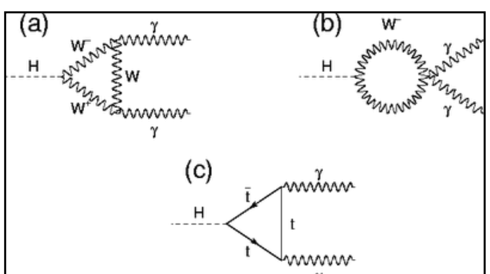
Lepton isolation criteria are also important to reject backgrounds from heavy flavour decays

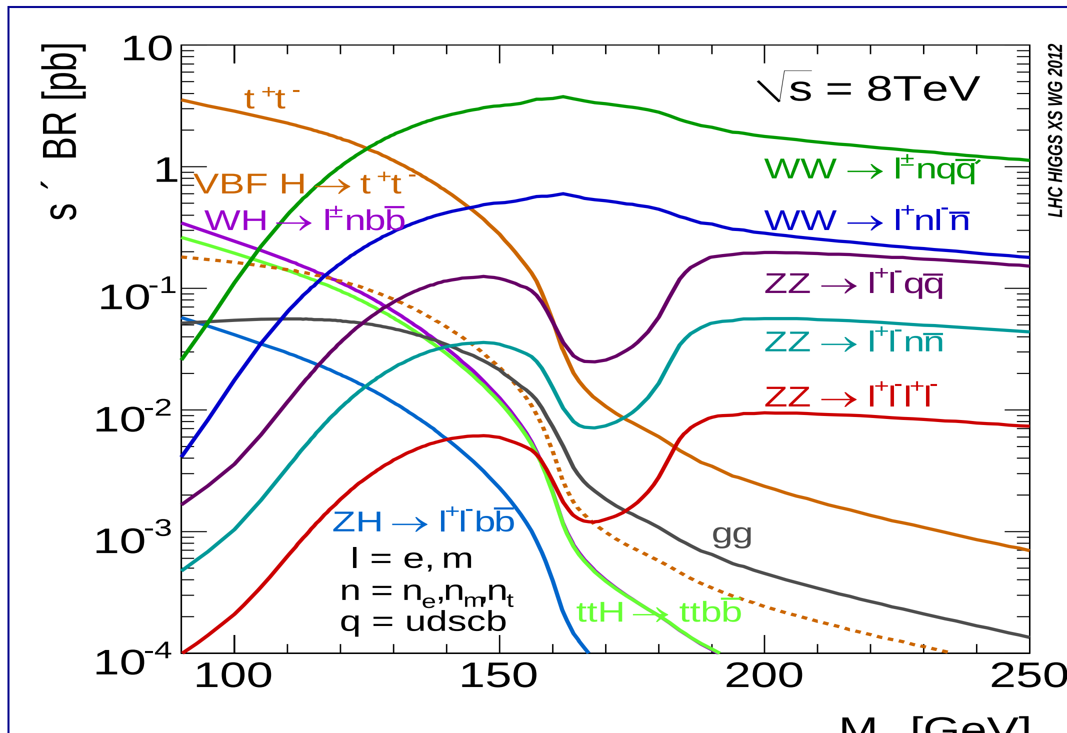
Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 8 TeV

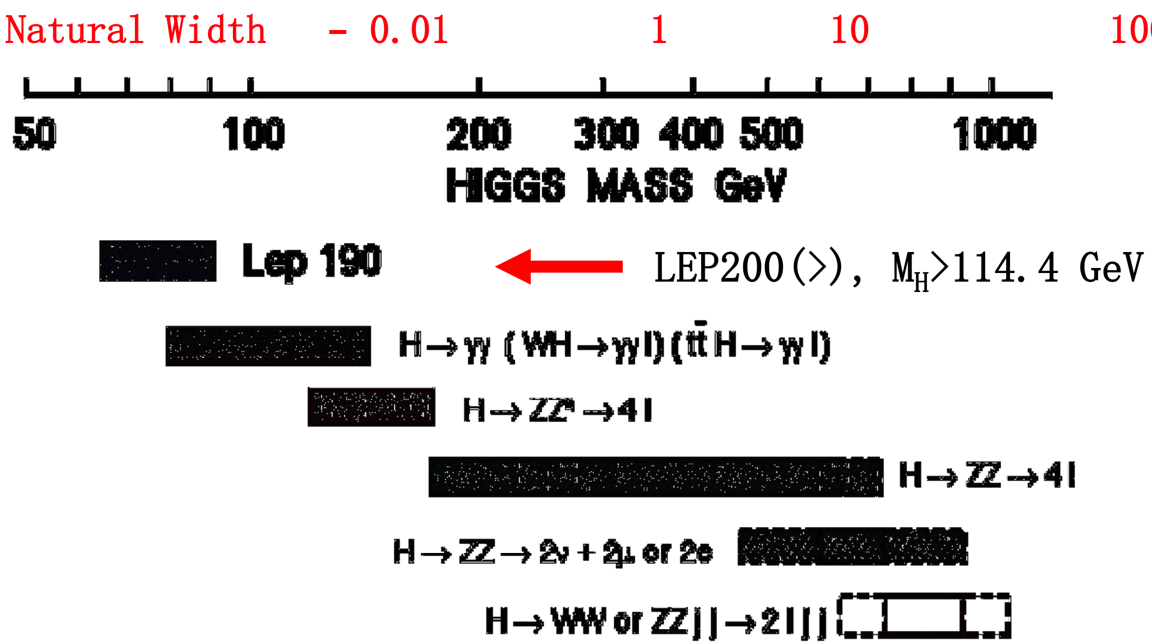


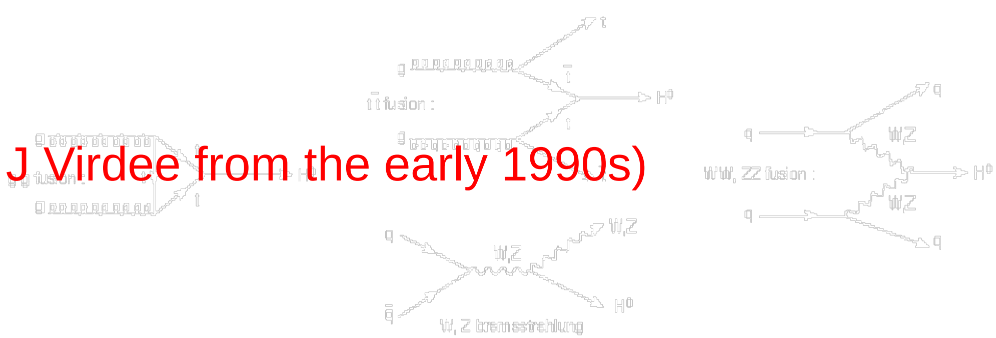






At the LHC the SM Higgs provides a good benchmark to test the performance of a detector





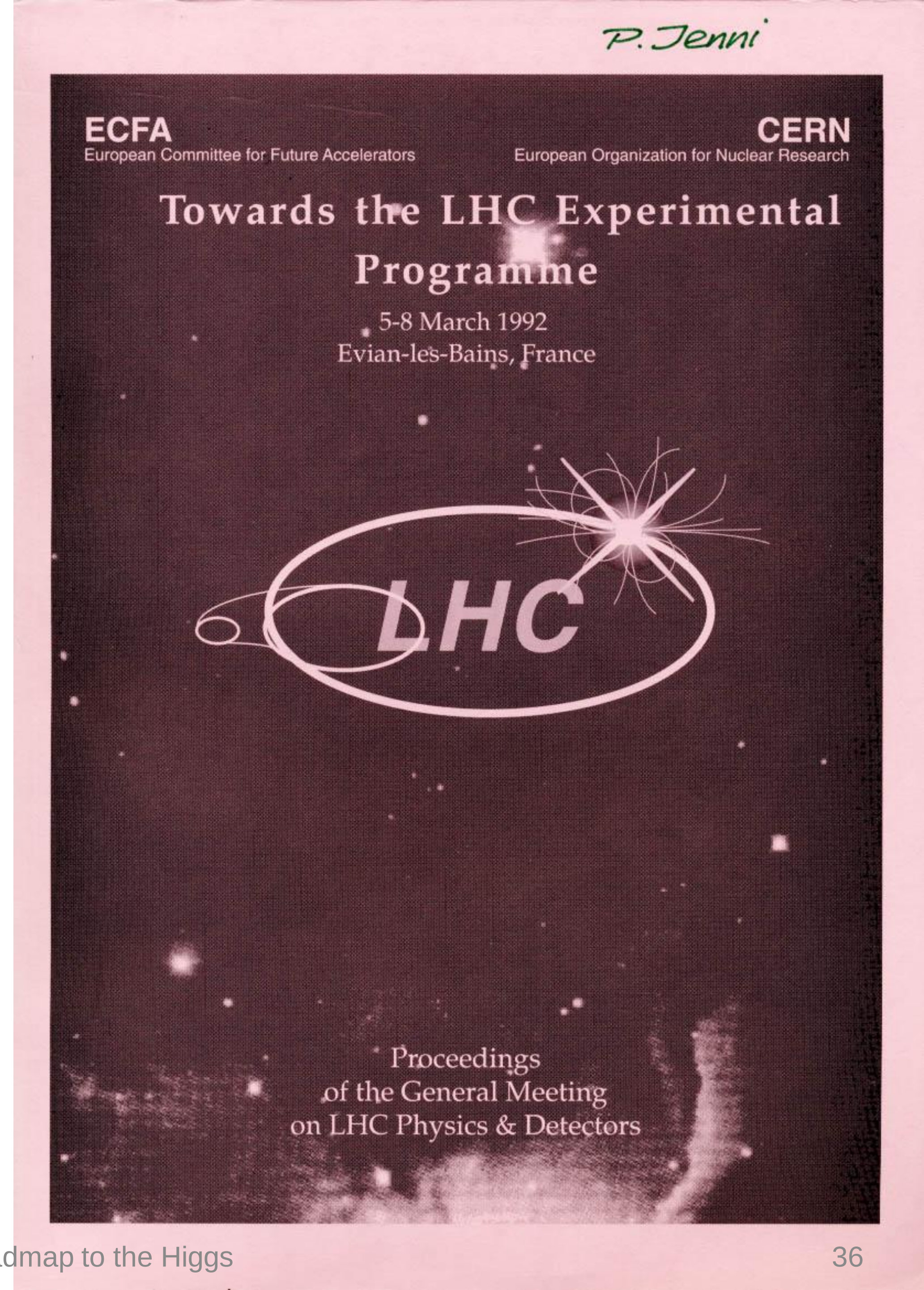
(A slide from J Virdee from the early 1990s)

March 1992

Evian Meeting with EoI presentations

ASCOT	pp	Norton
CMS	pp	Della Negra / Desportes
EAGLE	pp	PJ
L3+1	pp	Ting / Pauss

LHC Beauty Collider	Schlein
B extracted beam	Carboni
B gas jet	Nakada
Neutrino at LHC	Vannucci
LHC HI	Schukraft
DELPHI LHC HI	Jarlskog


P. Jenni

ECFA
European Committee for Future Accelerators

CERN
European Organization for Nuclear Research

Towards the LHC Experimental Programme

5-8 March 1992
Evian-les-Bains, France

LHC

Proceedings
of the General Meeting
on LHC Physics & Detectors

The birth of ATLAS

March 1992 – Summer 1992

Merging of EAGLE and ASCOT

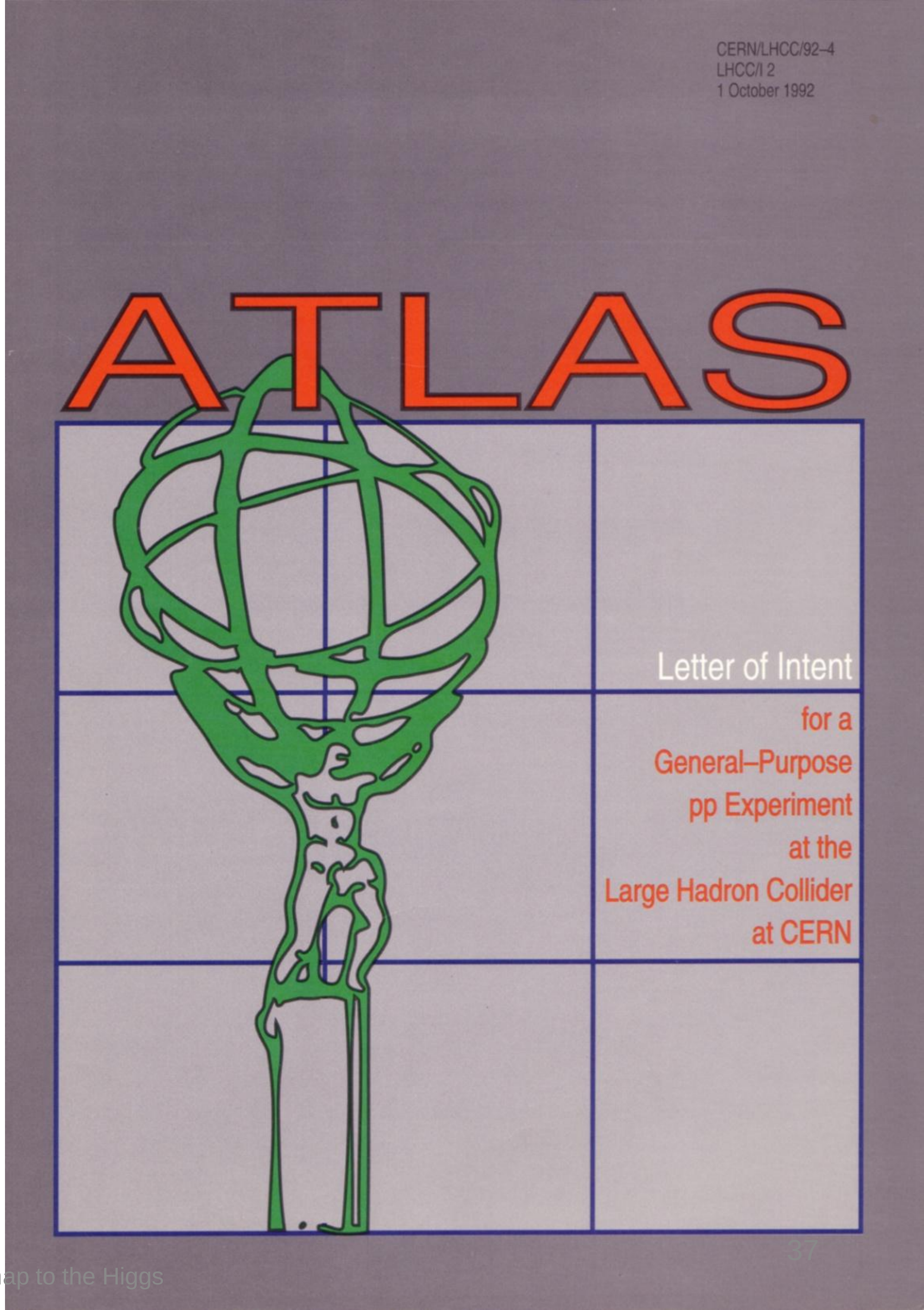
September 1992: Decision on the name

1st round		2nd round	
ATLAS	31	ATLAS	40
ALICE	12	ALICE	13
ACE	5		
ALEX	5		
LHD	0		

October 1992:

ATLAS LoI submitted to the LHCC

(as well as the CMS LoI)



The SM is not a complete theory

Some of the outstanding questions in fundamental physics were/are

(~✔) What is the origin of the elementary particle masses ?

What is the nature of the Universe dark matter ?

Why is only matter observed in the Universe as primary constituents and not anti-matter ?

What are the features of the primordial plasma present ~10 μs after the Big Bang ?

What happened in the first moments of the Universe ~10^{-11} s after the Big Bang ?

Are there other forces in addition to the known four ?

Are there additional (microscopic) space dimensions ?

....

ATLAS, CMS

ATLAS, CMS

LHCb

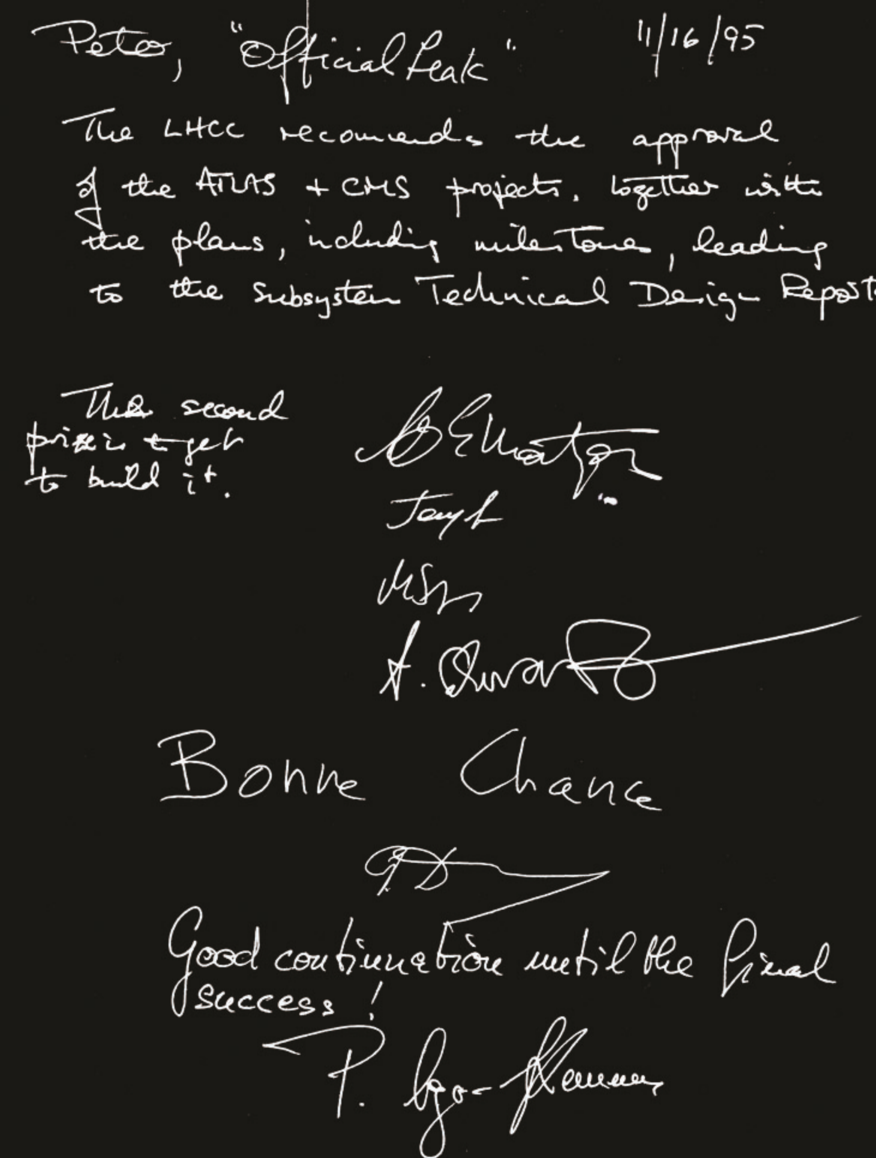
ALICE

ATLAS, CMS

ATLAS, CMS

For the experiments it was a long way convincing the LHCC, but finally, on 16th November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following 'official leak' from the committee…

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports



Peter, "Official Leak" 11/16/95

The LHCC recommends the approval of the ATLAS + CMS projects, together with the plans, including milestones, leading to the Subsystem Technical Design Reports

The second prize is to get to build it.

Bonne Chance

Good continuation until the final success!

Anything worked out fine, and we produced a large series of TDRs…

The formal construction approval was then given with the approval of the first TDRs, namely for the calorimeters

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
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E-mail: Christopher.Llewellyn.Smith@cern.ch

Dr Peter Jenni
PPE Division
CERN

Our Ref. DG/mnd/2540

Geneva, 1st July 1997

Dear Peter,

Following the thorough discussion of the status of ATLAS and CMS by Council and its Committees two weeks ago, the way is now open for construction to begin. I am therefore pleased to inform you that I have decided to *i)* set the cost ceiling for ATLAS at 475 MCHF (1995 prices), and *ii)* approve the TDR of the ATLAS calorimeters on the following basis formulated by the LHCC and endorsed by the Research Board at its meeting on 12th June:

*"The LHCC **recommends general approval** of the ATLAS Calorimetry Technical Design Report describing design, performance, construction, and installation in 2004. The review **identified some concerns** in limited areas, which require resolution (LHCC 97–27). The LHCC considers that the schedules and milestones given in the TDR are reasonable, and these will be used by the committee to measure and regulate the future progress of the project."*

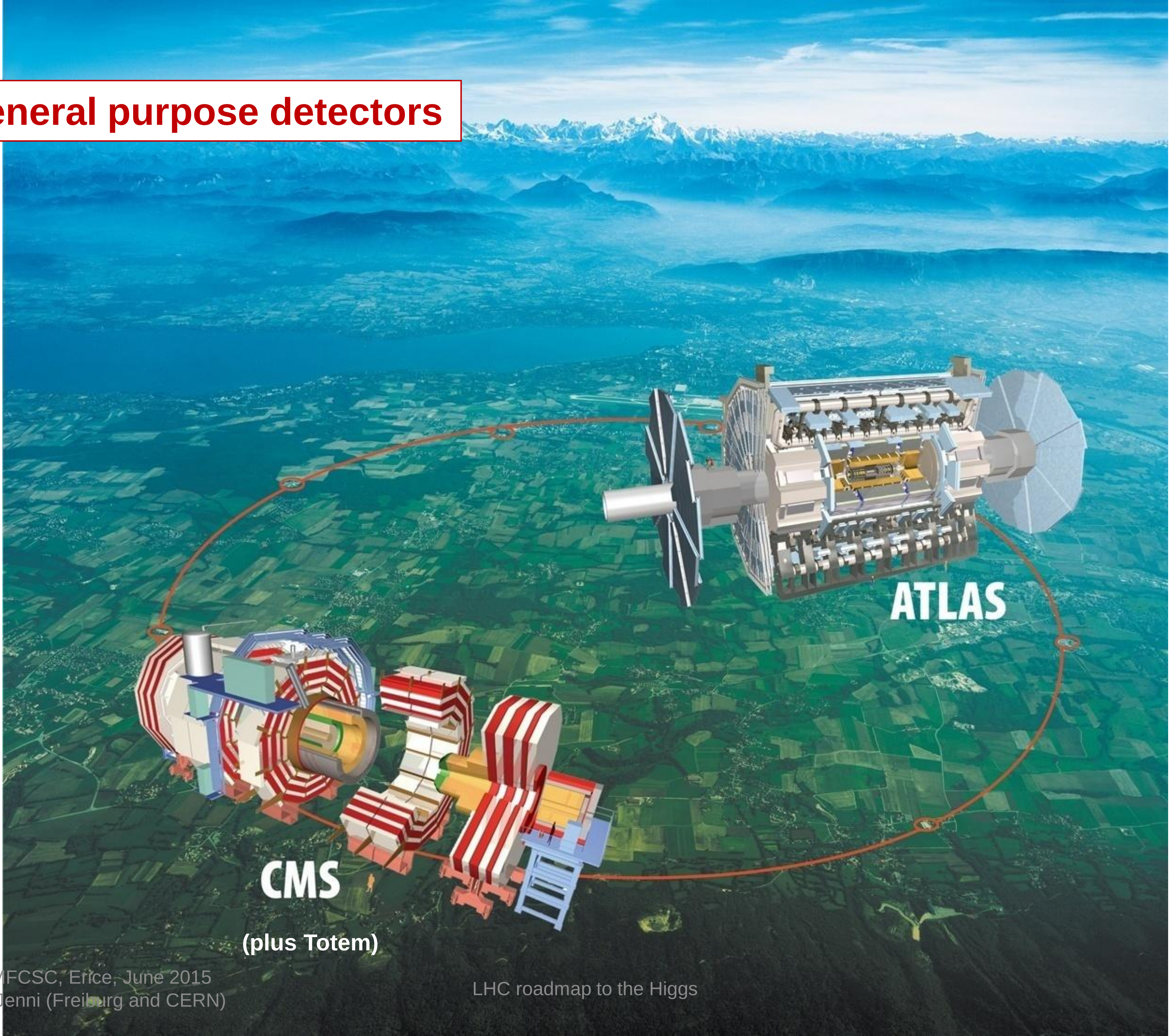
Yours sincerely,

Chris

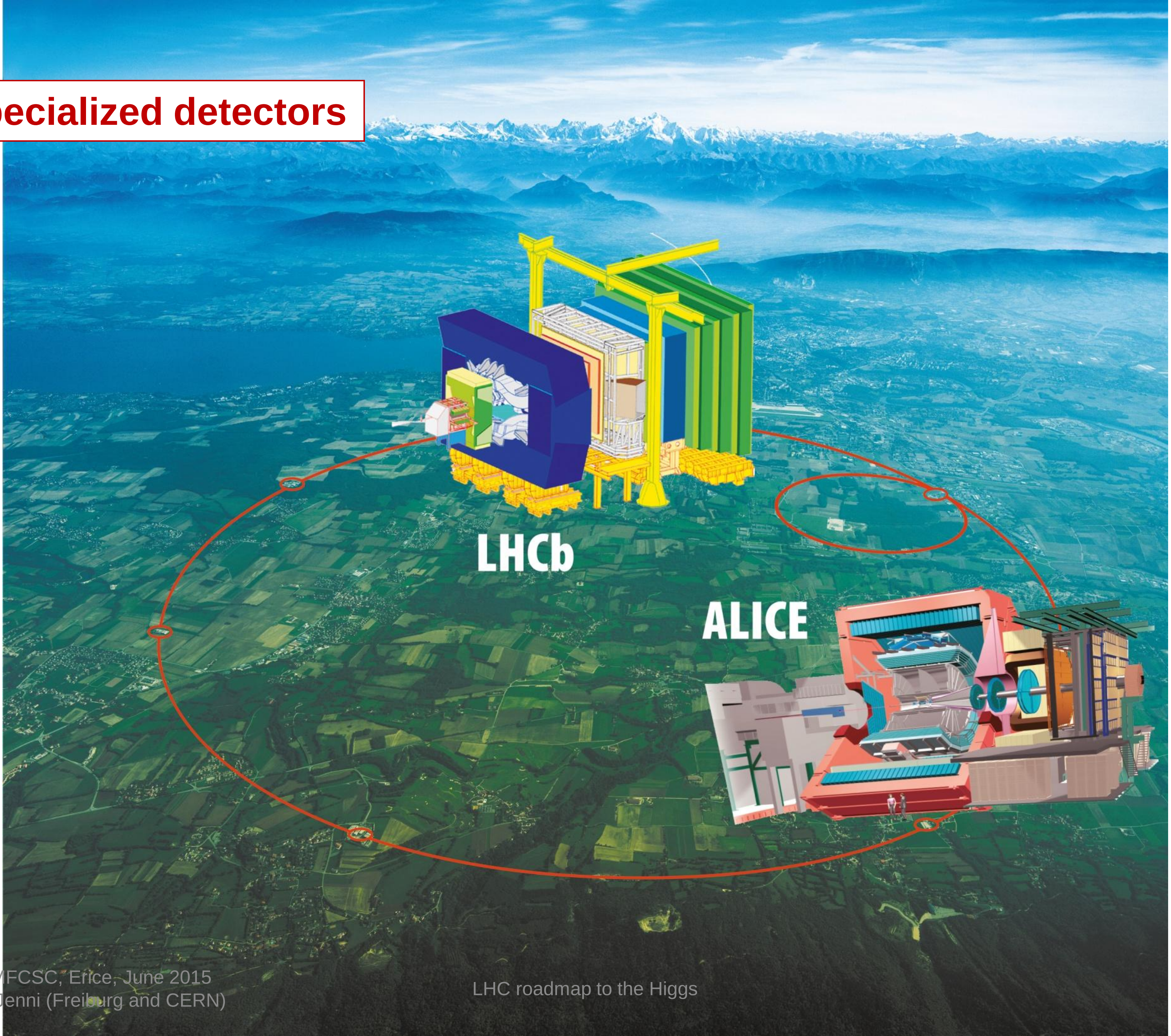
Chris Llewellyn Smith

cc: L Foà
E Iarocci

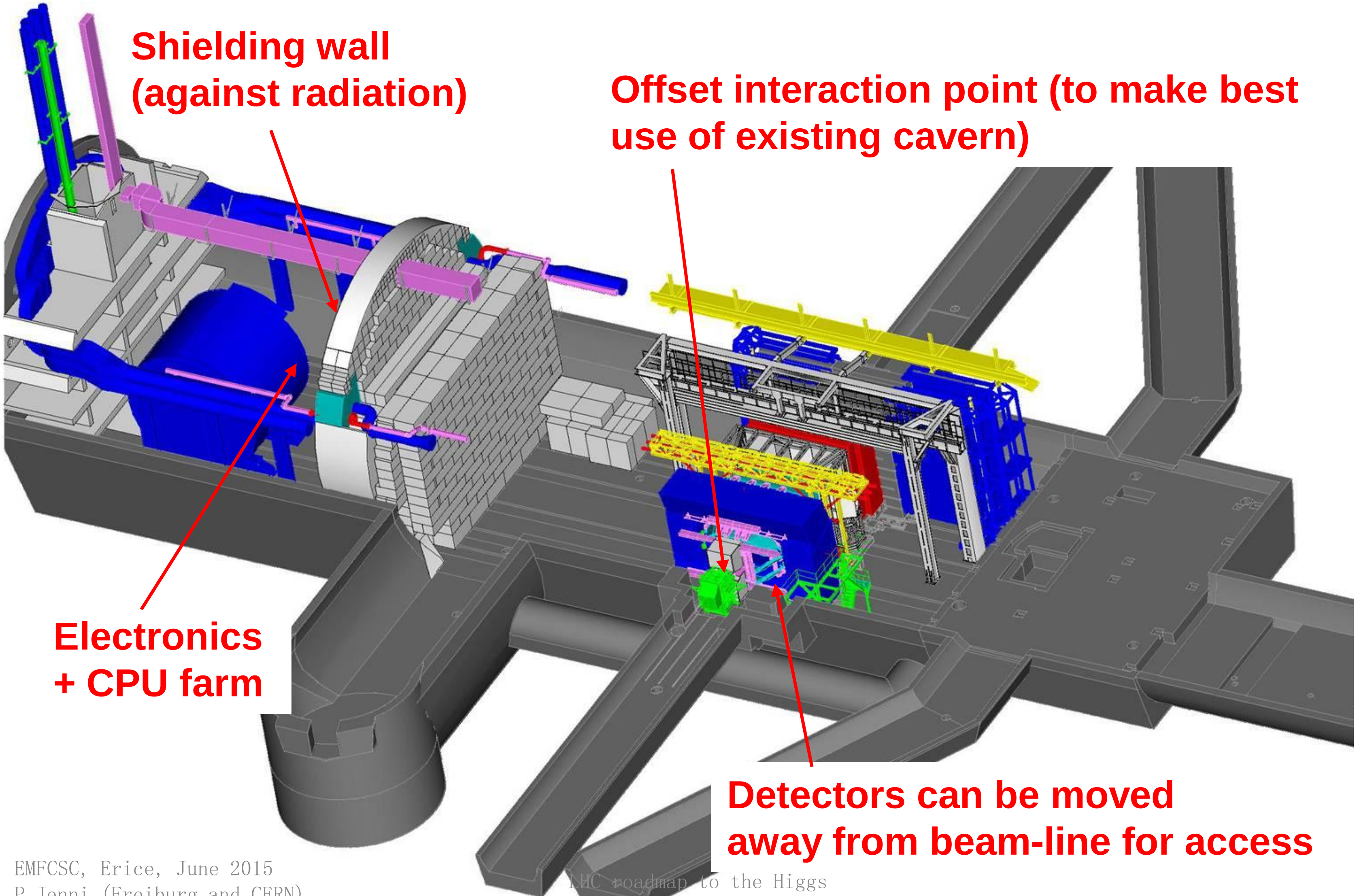
General purpose detectors



Specialized detectors



LHCb in its cavern (~100 m deep)



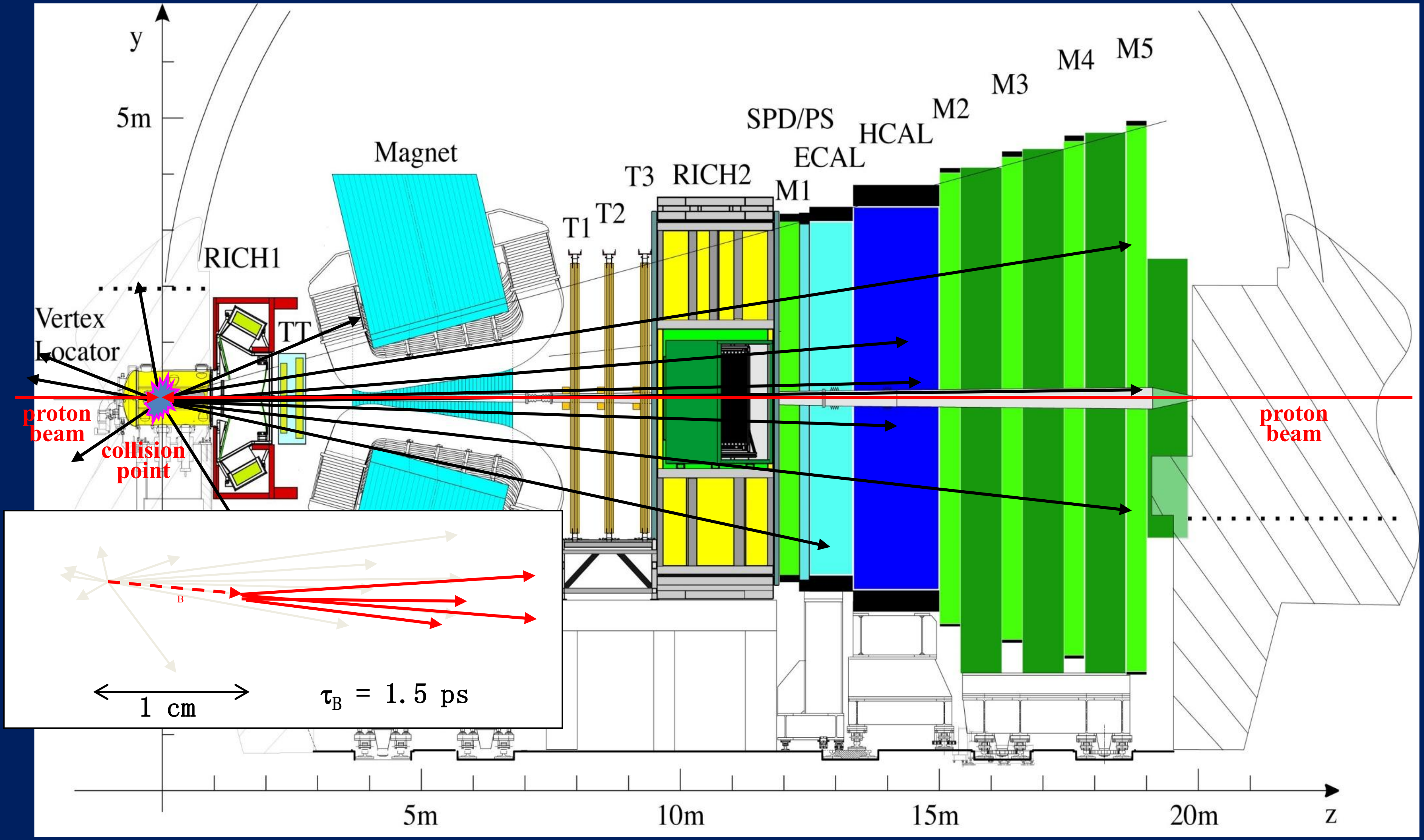
Shielding wall (against radiation)

Offset interaction point (to make best use of existing cavern)

Electronics + CPU farm

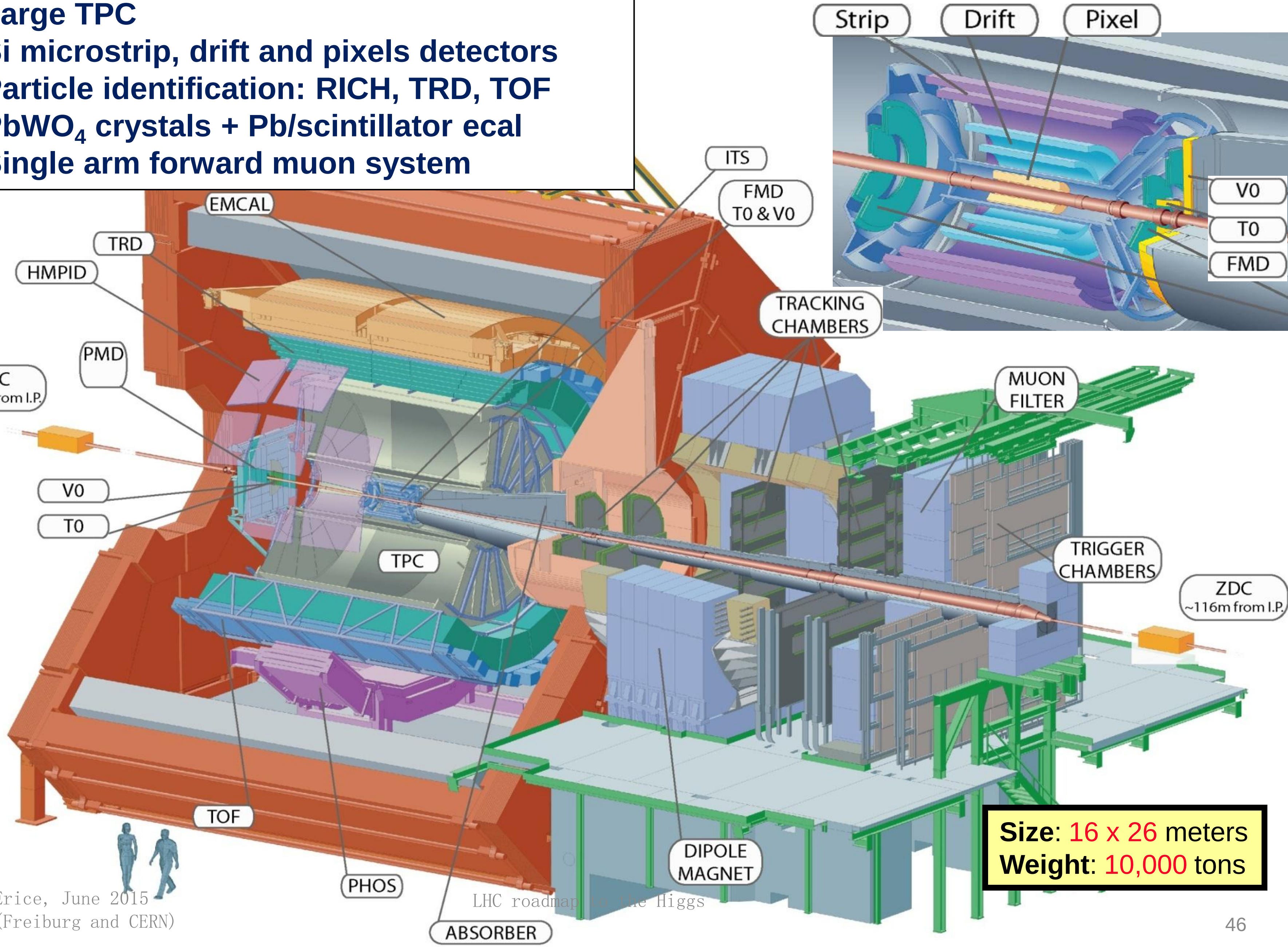
Detectors can be moved away from beam-line for access

The LHCb experiment

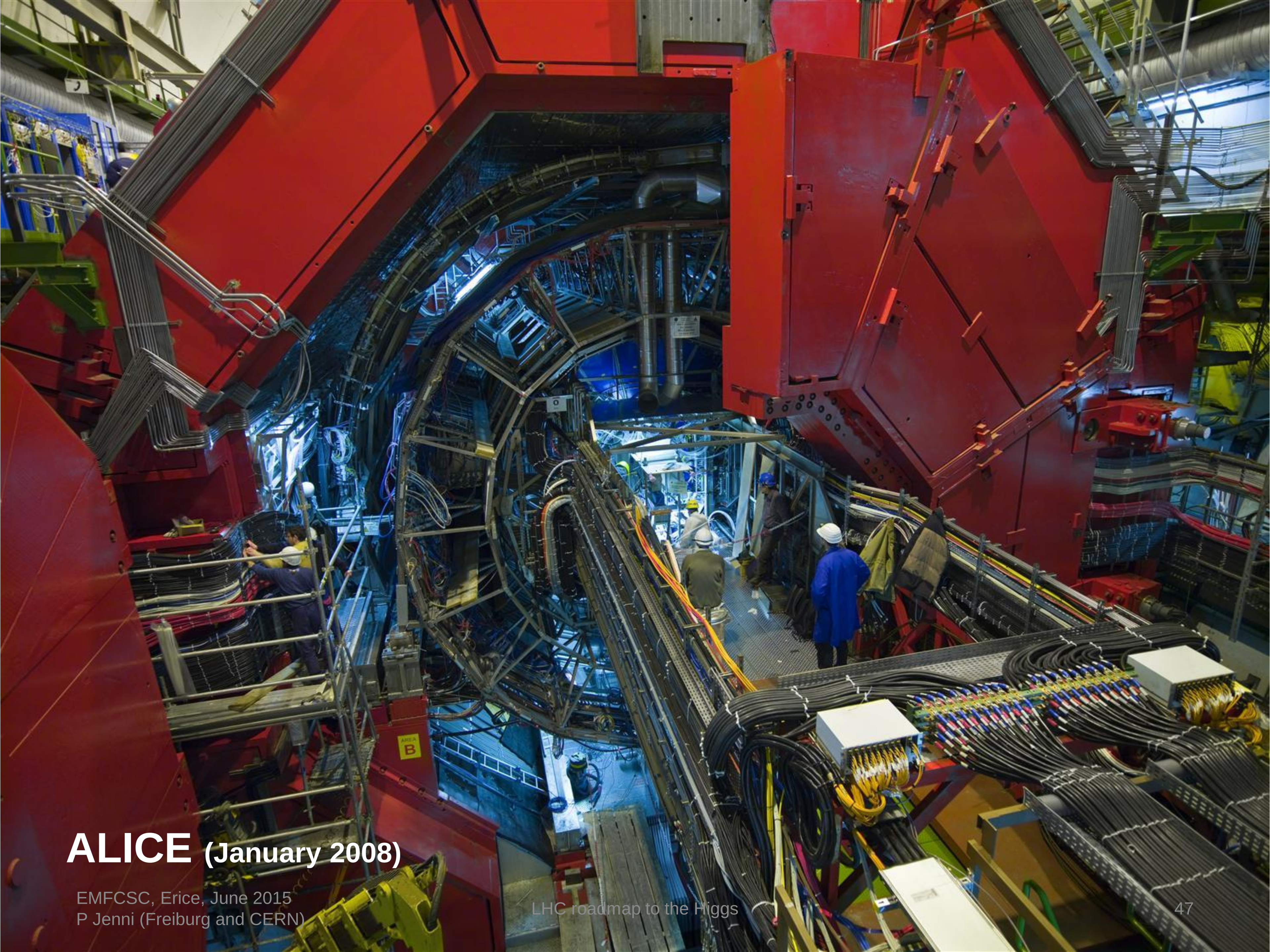


ALICE: study of quark-gluon plasma

- L3 solenoid
- Large TPC
- Si microstrip, drift and pixels detectors
- Particle identification: RICH, TRD, TOF
- $PbWO_4$ crystals + Pb/scintillator ecal
- Single arm forward muon system



Size: 16 x 26 meters
Weight: 10,000 tons

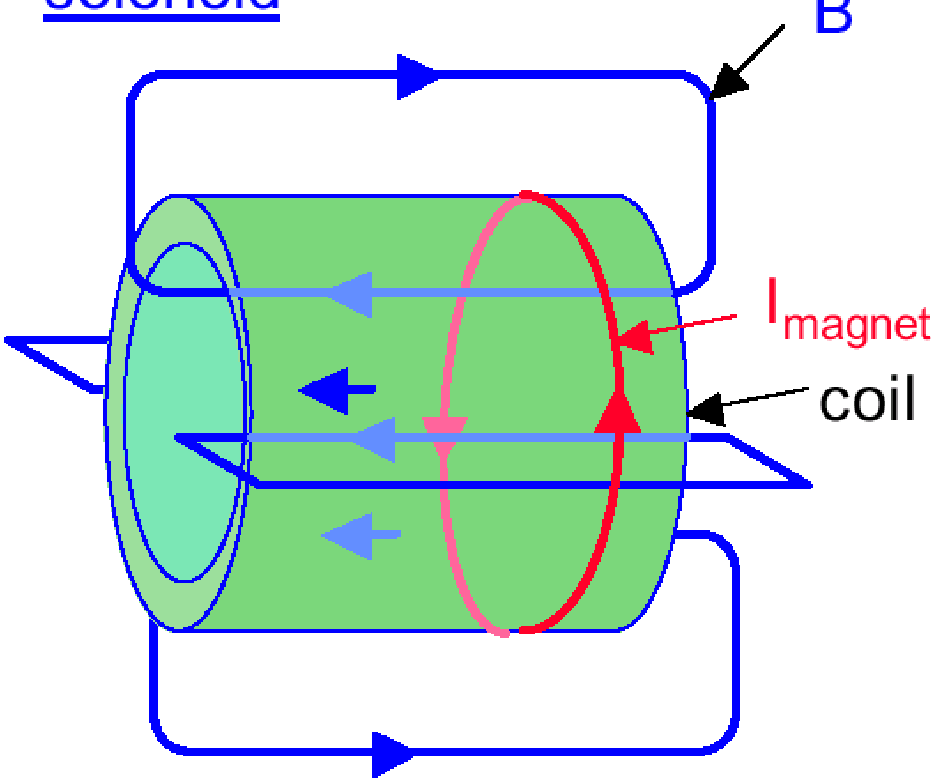


ALICE (January 2008)

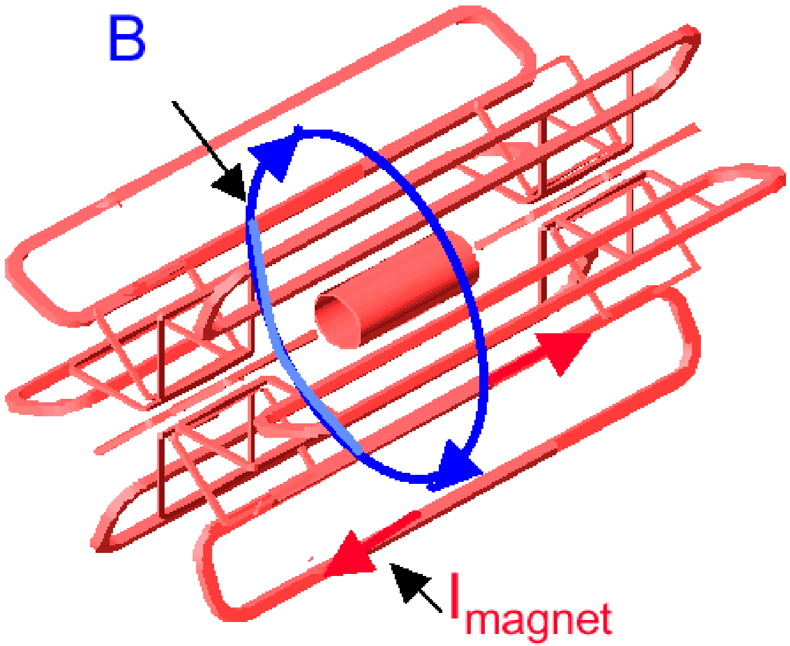
Magnetic fields

Magnetic field configurations:

solenoid

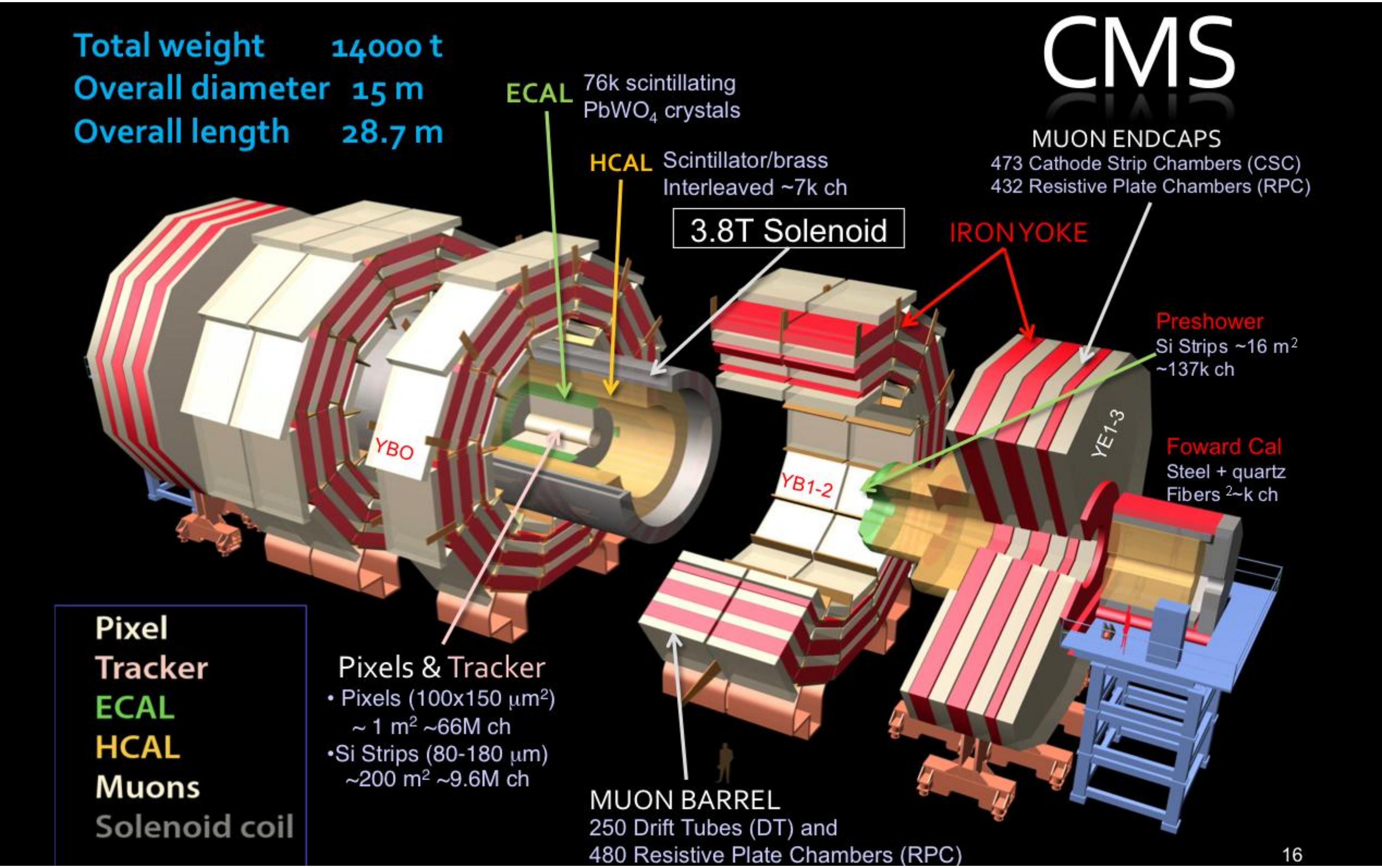


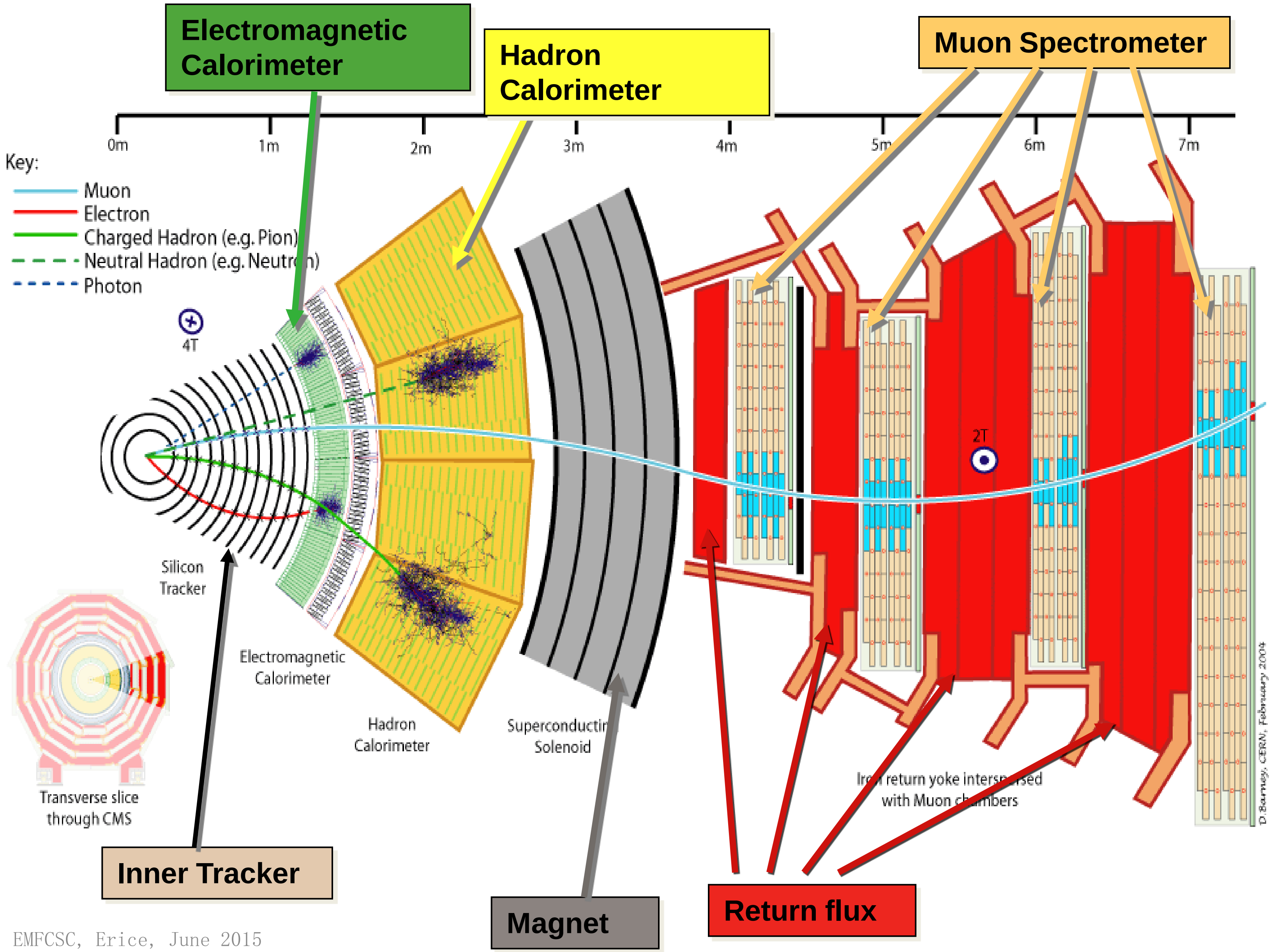
toroid



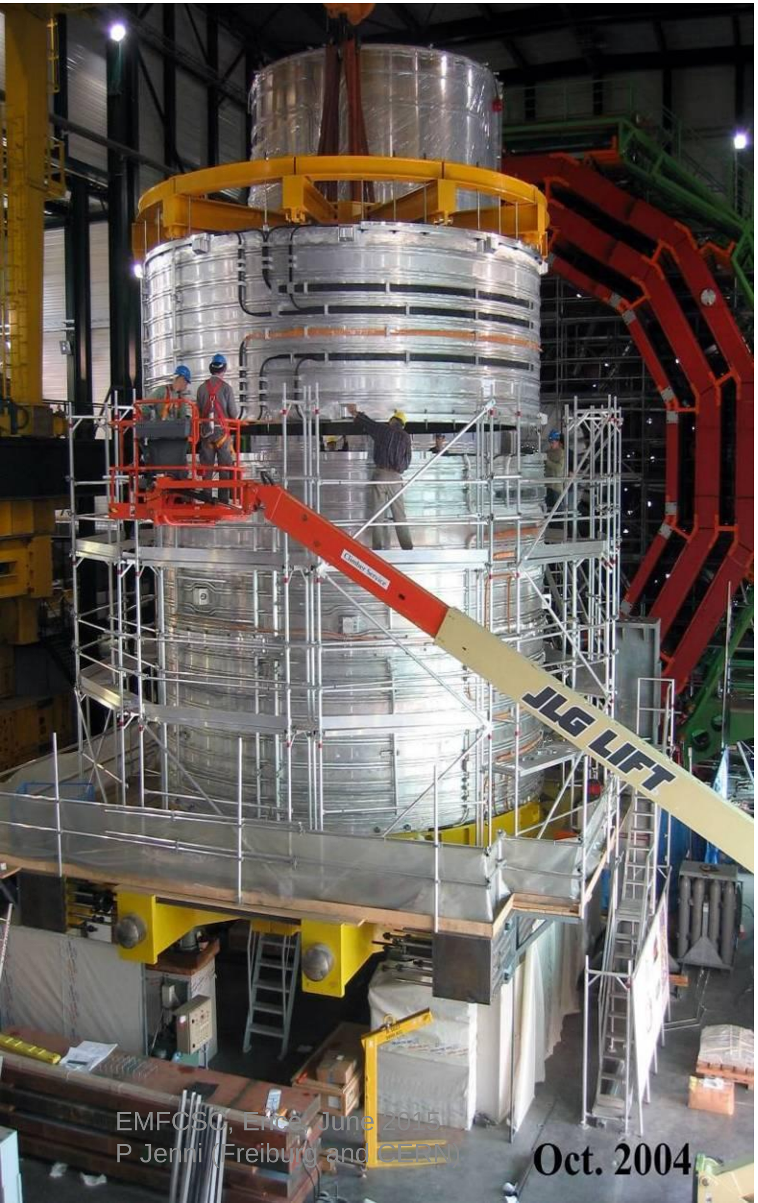
From C.Joram

Exploded View of CMS




Electromagnetic Calorimeter
Hadron Calorimeter
Muon Spectrometer
0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004
Inner Tracker
Magnet
Return flux

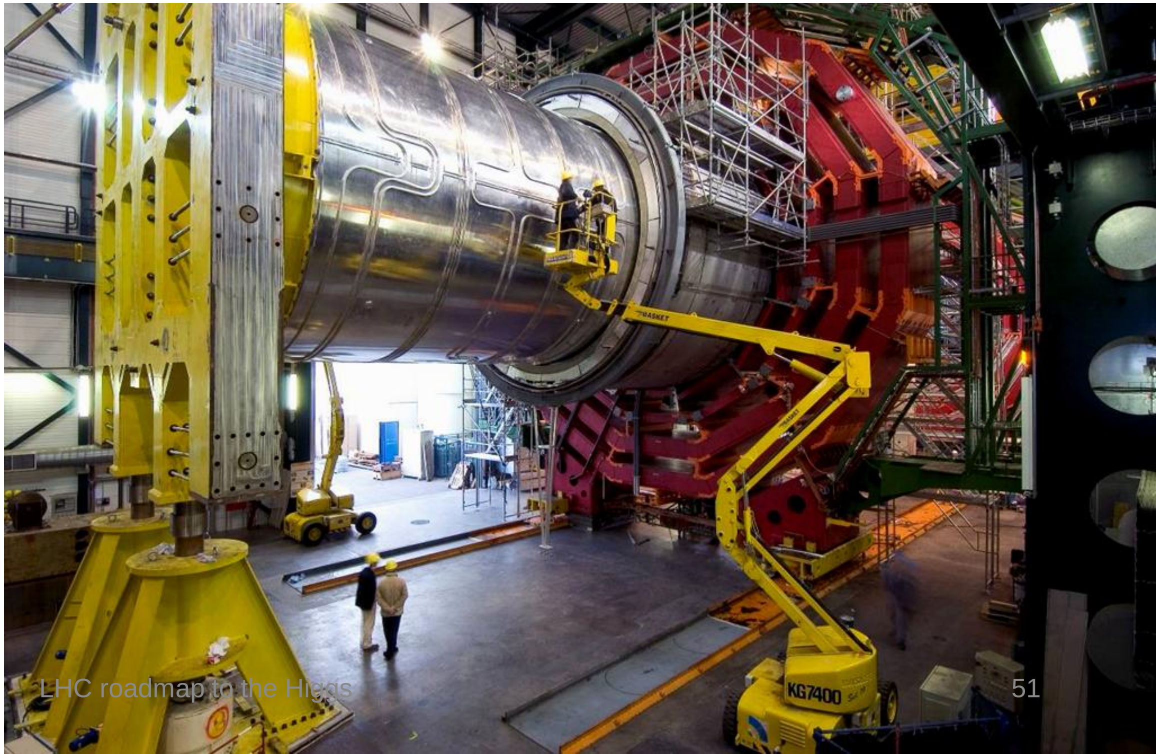
An Example of an Engineering Challenge: CMS Solenoid



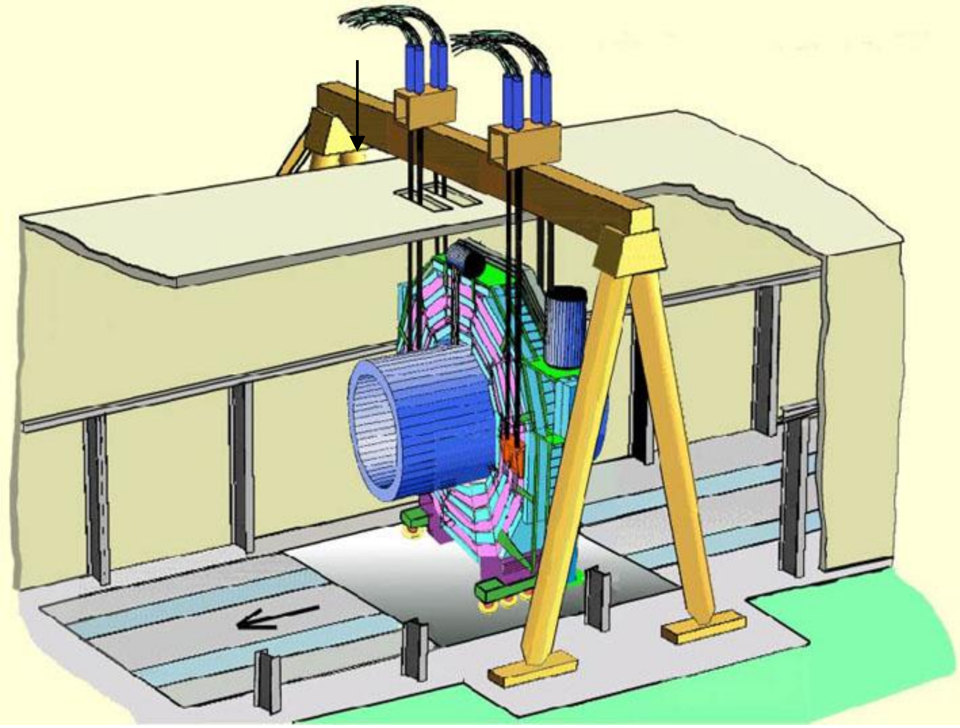
CMS solenoid:

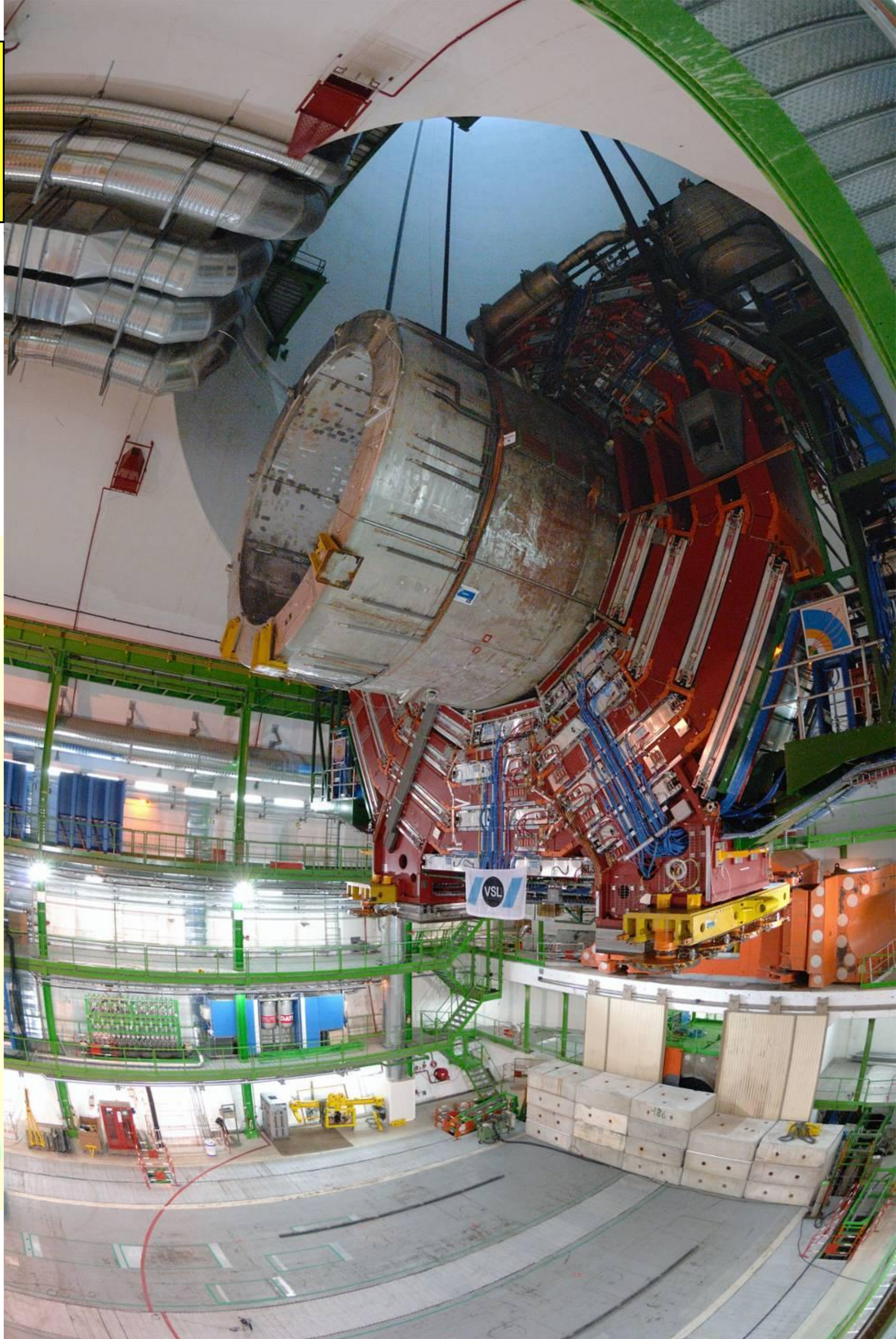
Magnetic length	12.5 m
Diameter	6 m
Magnetic field	4 T
Nominal current	20 kA
Stored energy	2.7 GJ

Tested at full current in Summer 2006



The central, heaviest slice (2000 tons) including the solenoid magnet lowered in the underground cavern in Feb. 2007





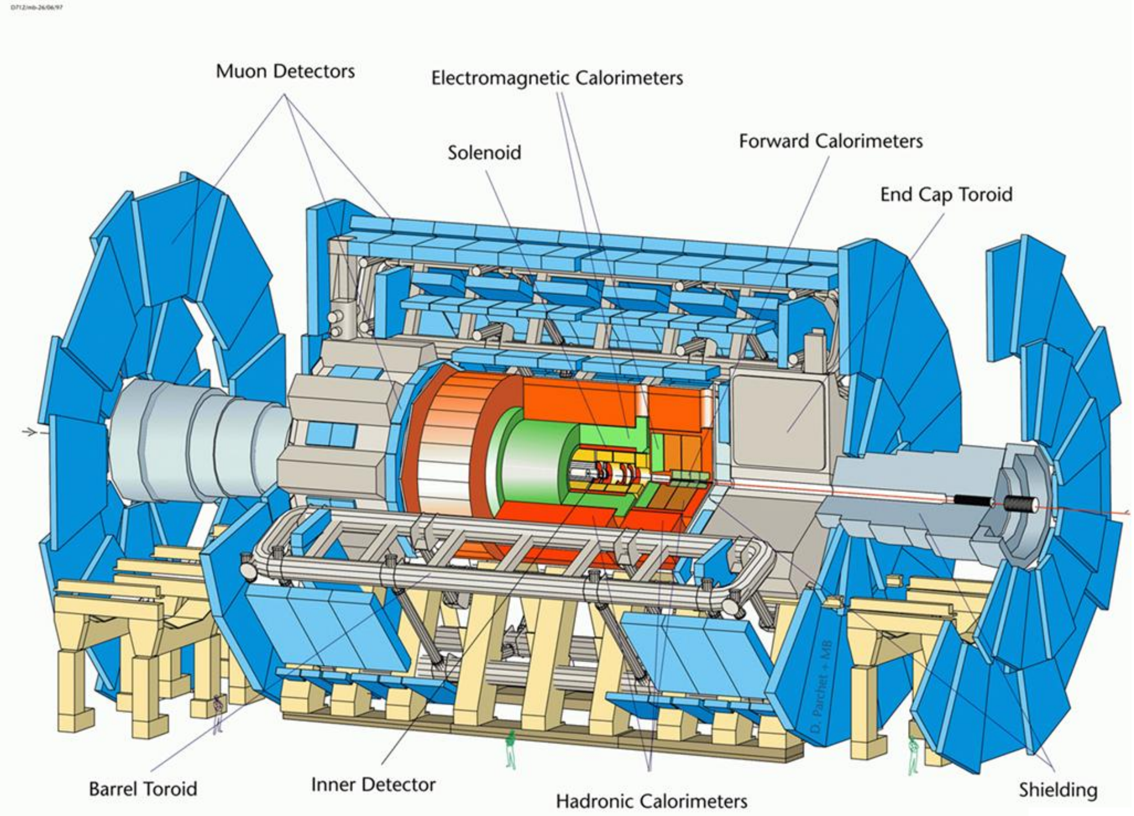
CMS before closure 2008

As an example:

ATLAS Collaboration

39 Countries
178 Institutions
3000 Scientific participants total
(1000 Students)

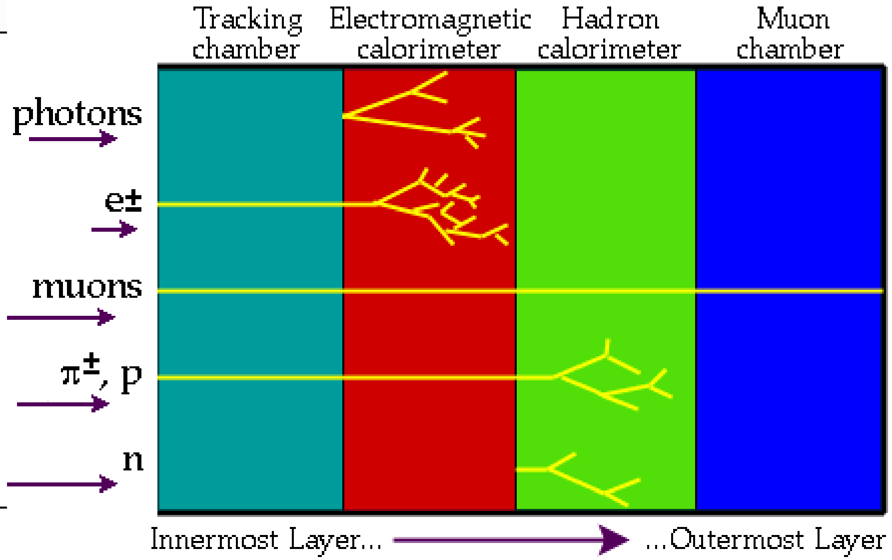
Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Hong Kong, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan



ATLAS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

- **Tracking (|η|<2.5, B=2T) :**
  - -- Si pixels and strips
  - -- Transition Radiation Detector (e/π separation)
- **Calorimetry (|η|<5) :**
  - -- EM : Pb-LAr
  - -- HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- **Muon Spectrometer (|η|<2.7) :**
  air-core toroids with muon chambers



Complementary Approaches in ATLAS and CMS

	ATLAS ≡ A Toroidal LHC ApparatuS	CMS ≡ Compact Muon Solenoid
MAGNET (S)	Air-core toroids + solenoid in inner cavity (4 magnets) Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T \oplus 0.015$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim$ 10 % at 1 TeV standalone (~ 7% combined with tracker)	Fe → $\sigma/p_T \sim$ 15-30% at 1 TeV standalone (5% with tracker)

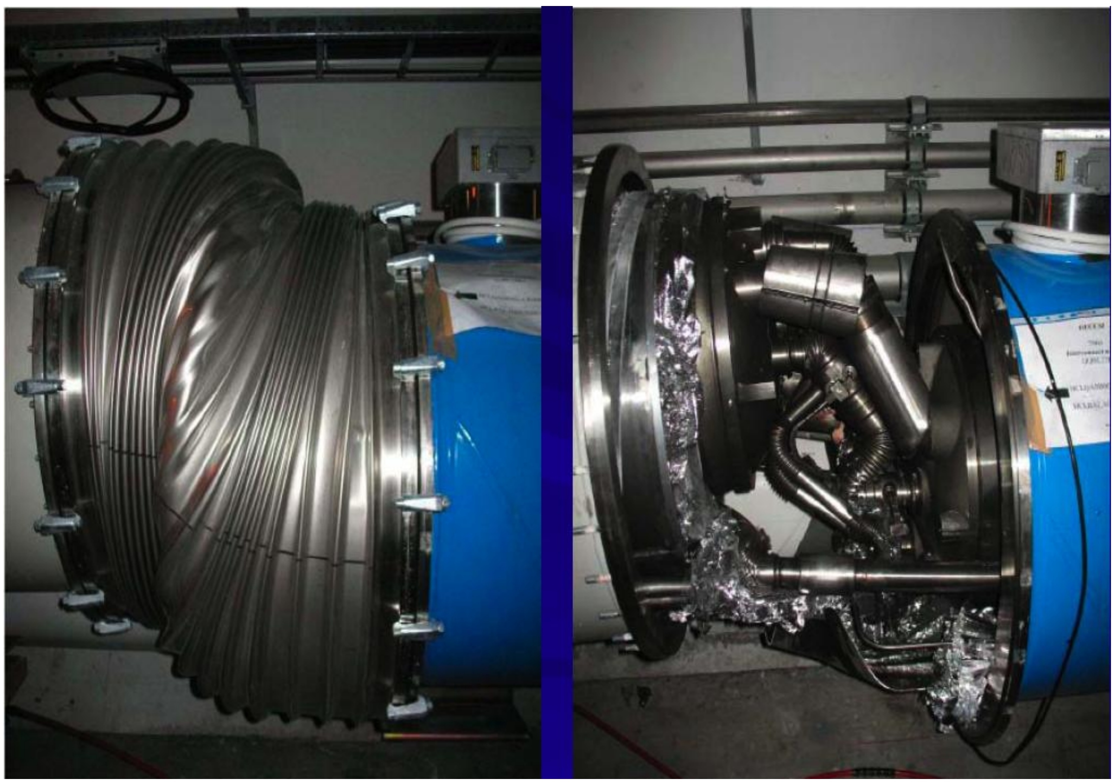
Interconnections of two magnets

One (superconductor) joint failed on 19th September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

Examples of collateral damage

High pressure build-up damaged the magnet interconnects and the super-insulation

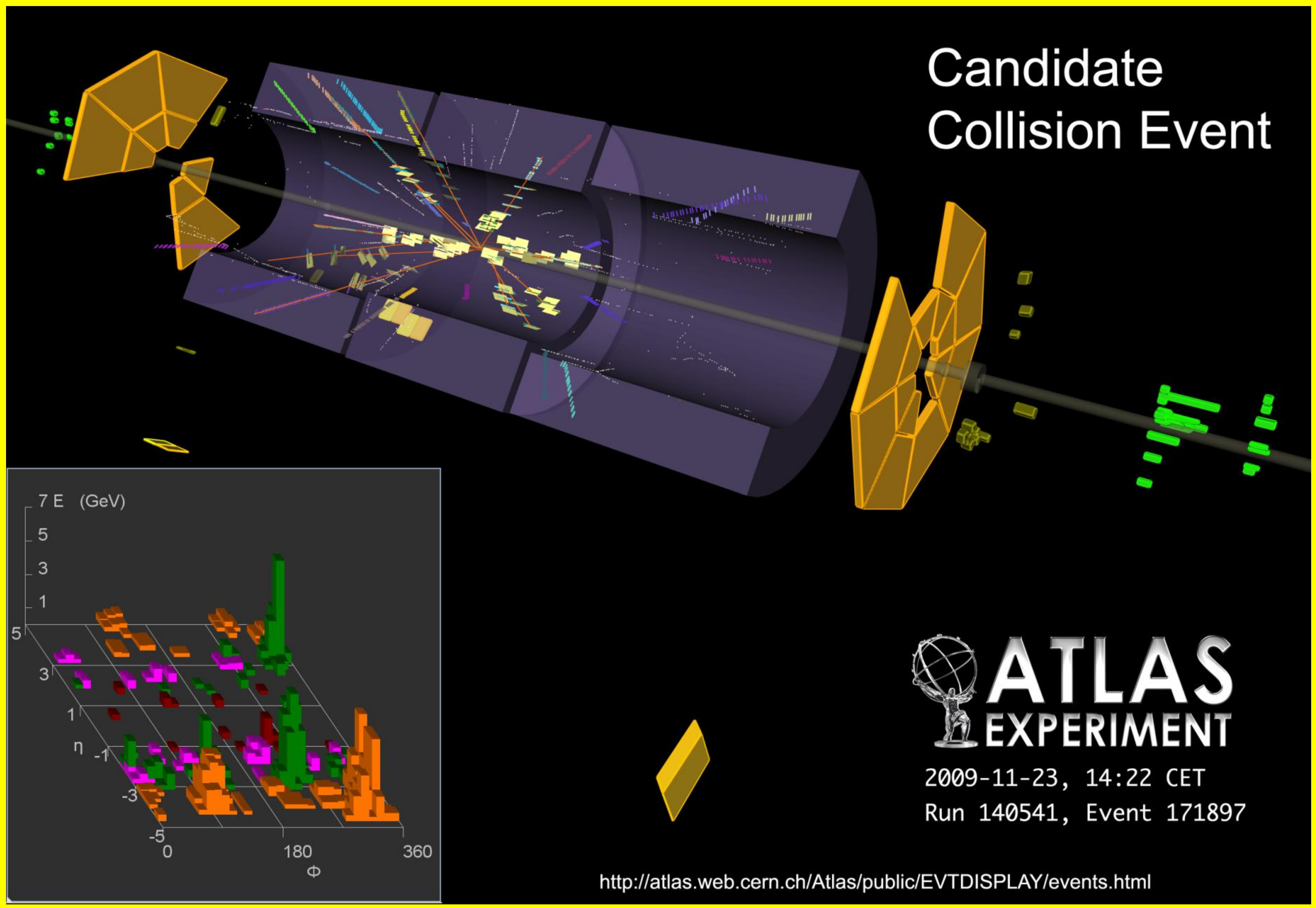
Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.

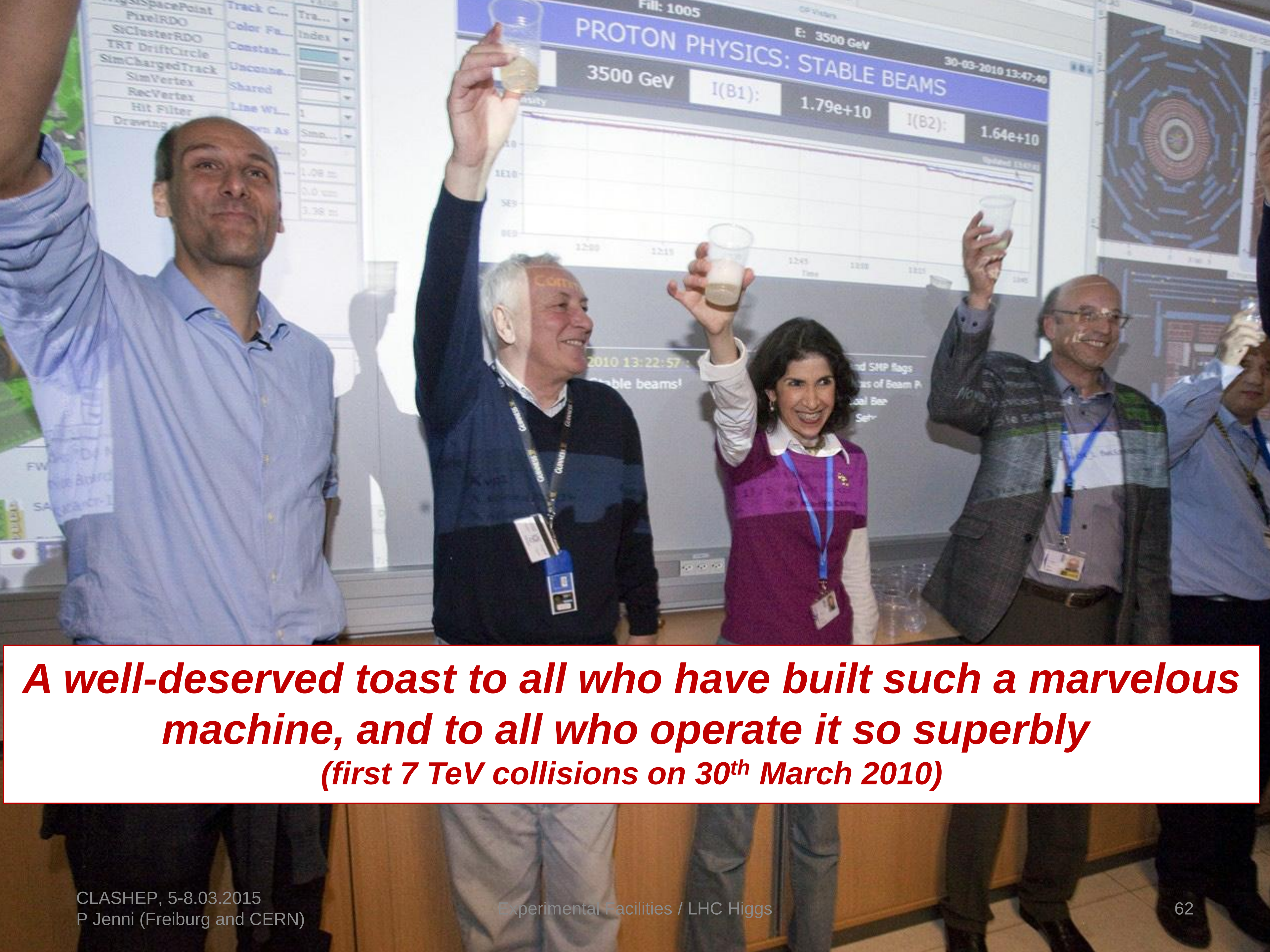


Expecting in the ATLAS Control Room the first LHC beam to collide on November 23rd, 2009....

The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....

First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV





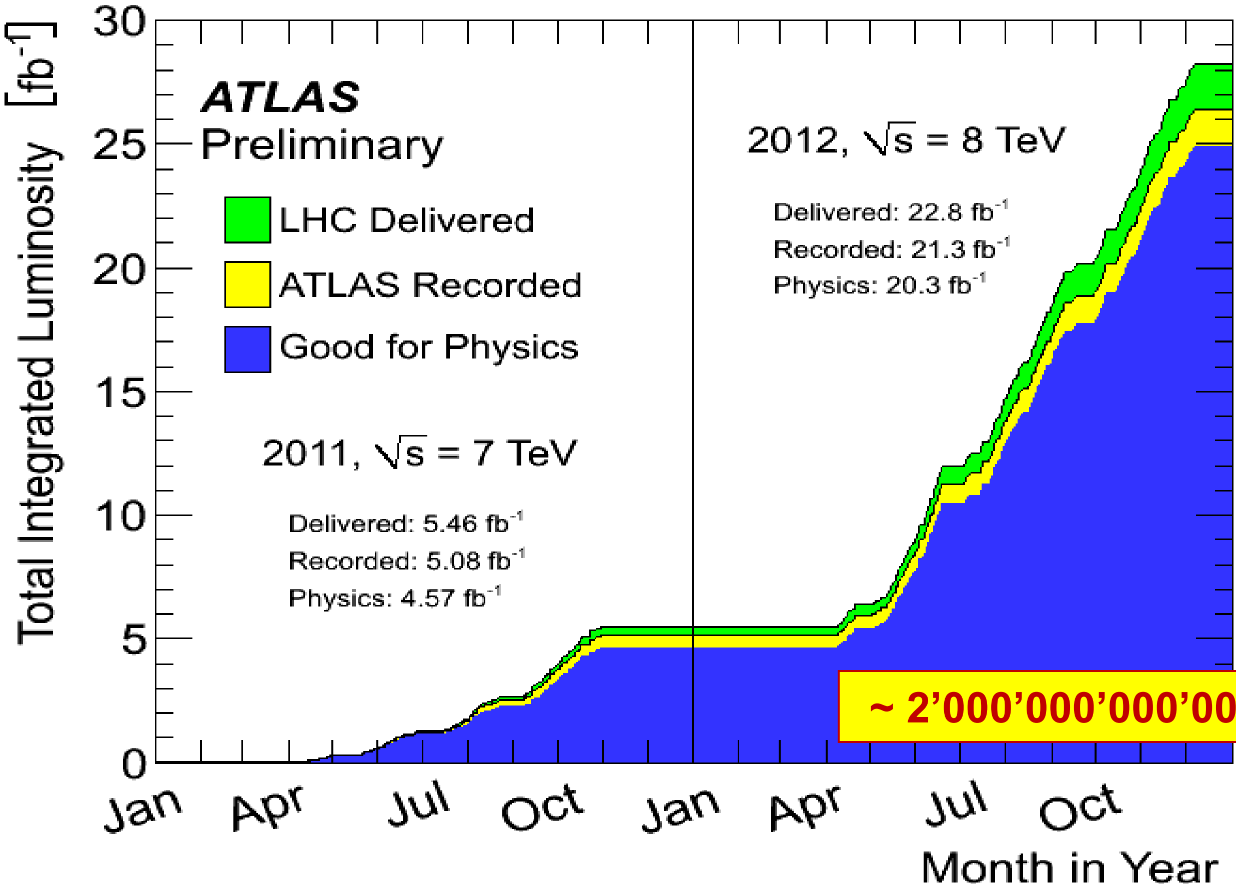
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

(first 7 TeV collisions on 30th March 2010)

The LHC and experiments performances were simply fantastic over the years 2010 – 2012 (Run-1)

Total integrated luminosity

$$N_{events} = \sigma \int L\, dt$$

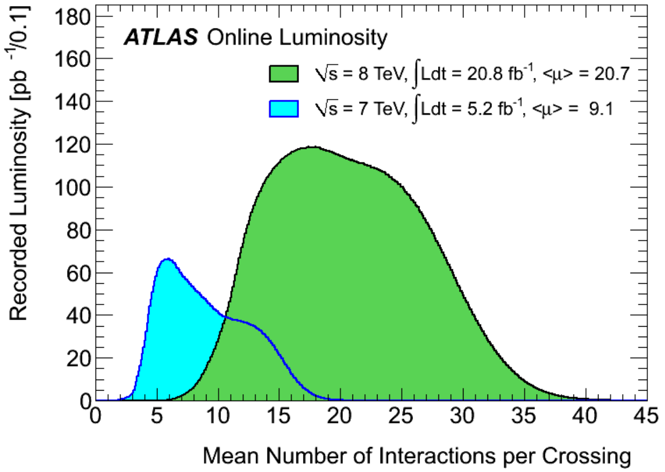


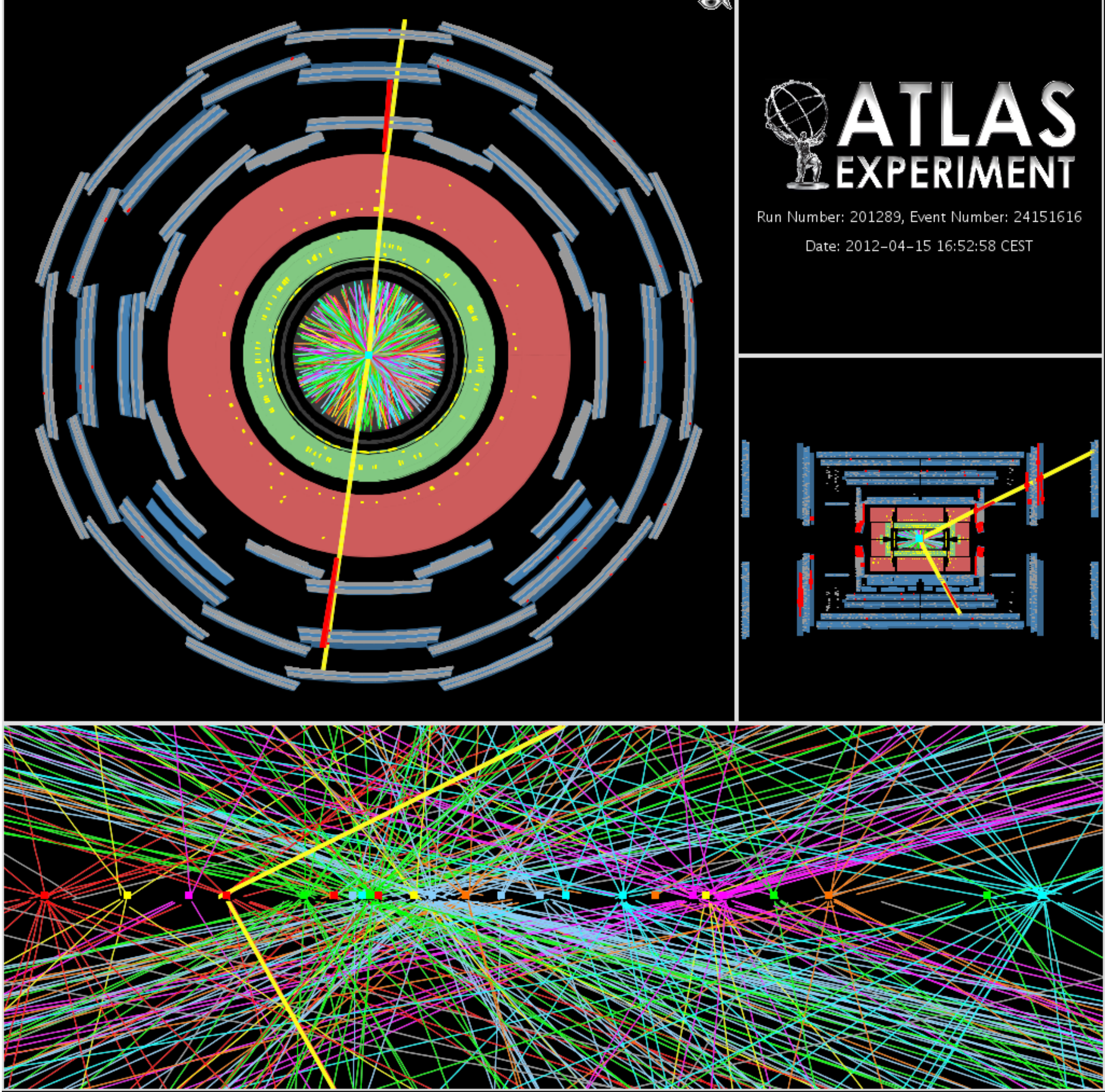
~ 2’000’000’000’000’000 collisions

The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!

Excellent LHC performance is a (nice) challenge for the experiment:

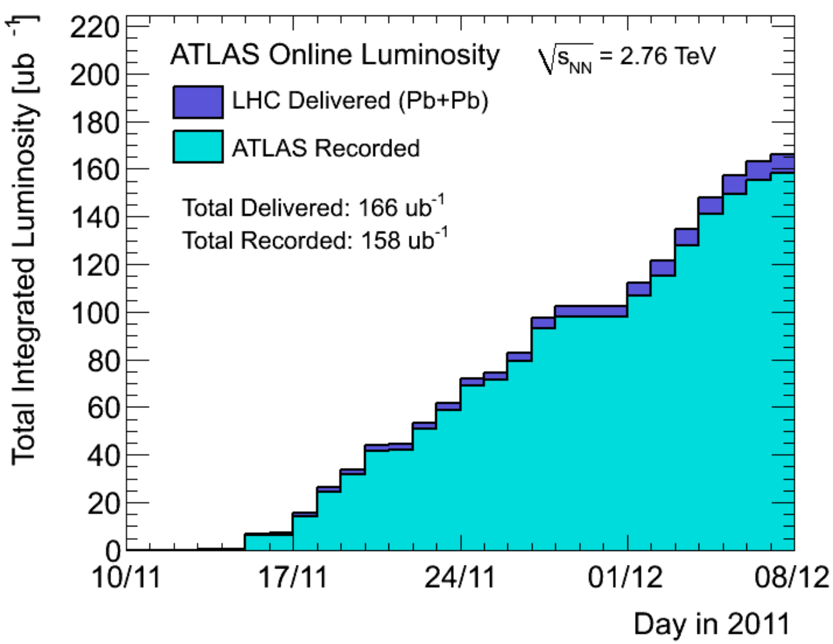
- Trigger
- Pile-up
- Maintain accuracy of the the measurements in this environment

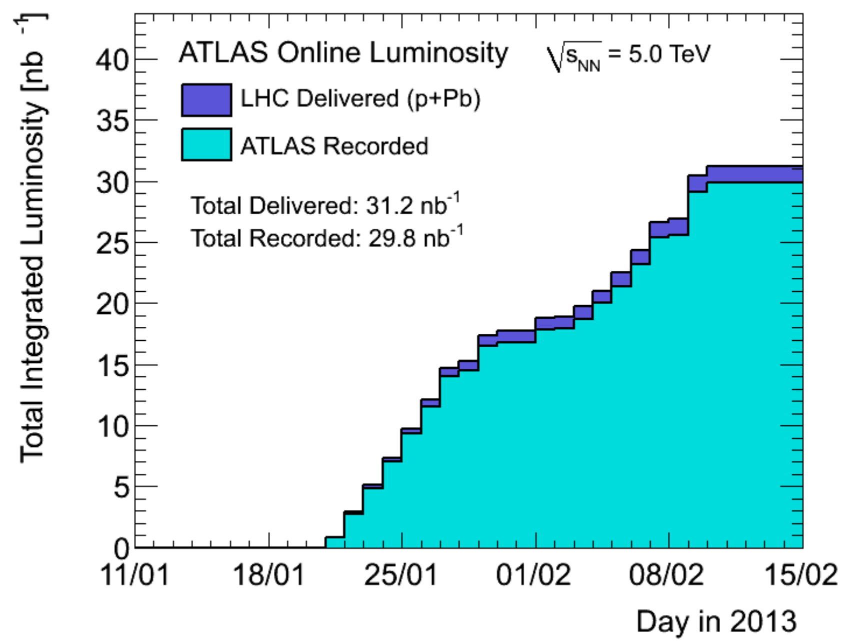




Inner Detector for a Z → μμ event with 25 primary vertices

LHC has also been operated very successfully as Pb-Pb (ALICE, ATLAS and CMS) and as p-Pb (all experiments) colliders





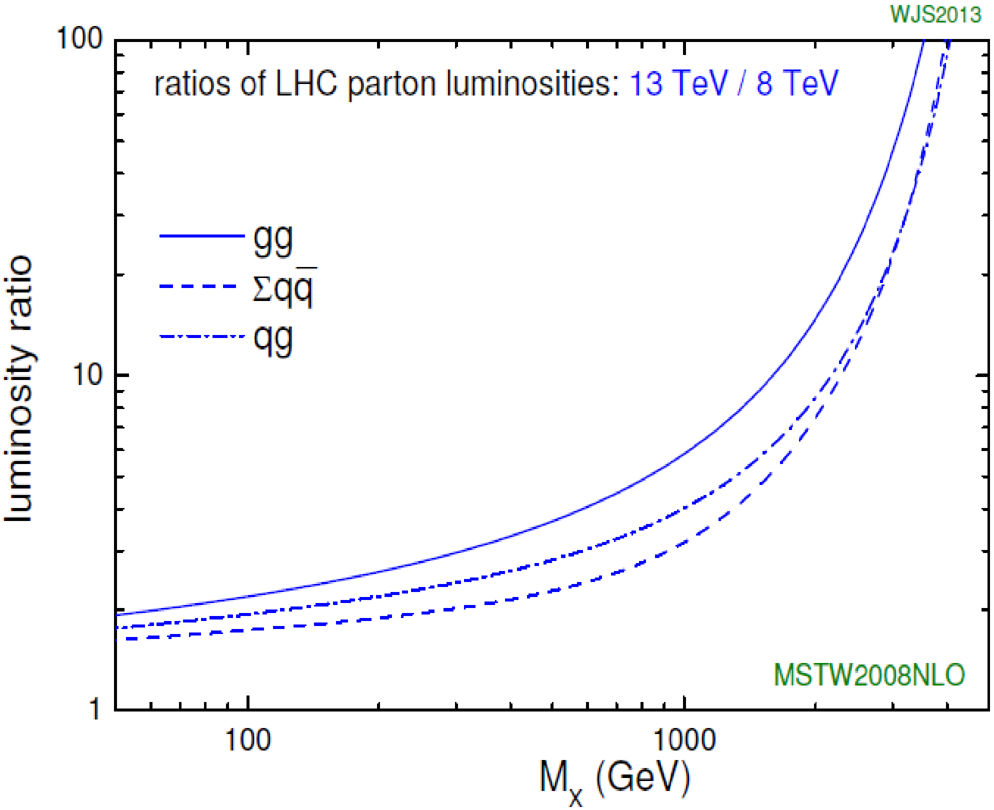
Pb nuclei are fully stripped: $^{208}Pb^{82+}$

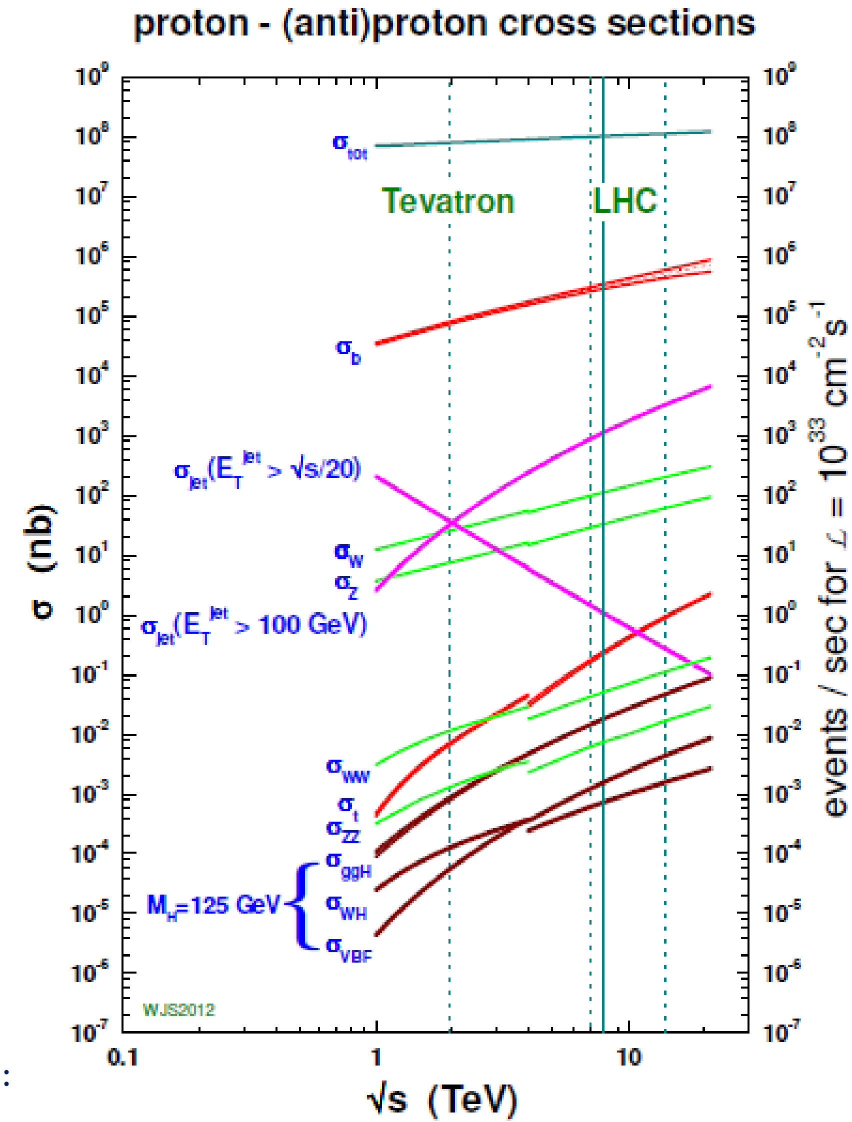
The collision energy is quoted usually per nucleon:
2.76 TeV = 7 TeV (pp) x 82 (charge) / 208 (nucleons)

Run-1 LHC parameters

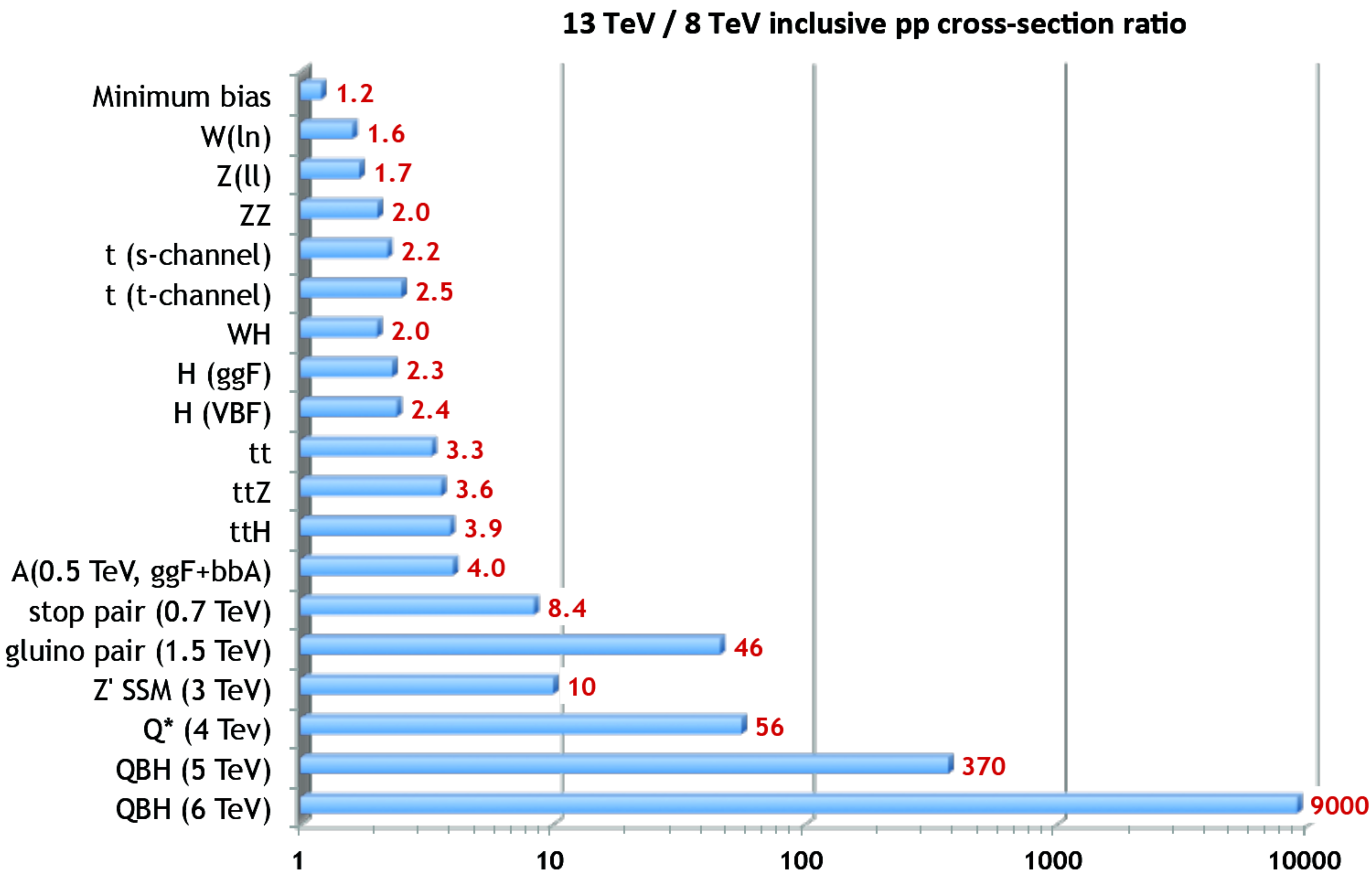
Parameter	2010	2011	2012	Nominal
beam energy (TeV)	3.5	3.5	4.0	7.0
bunch spacing	150	75 / 50	50	25
k (no. bunches)	368	1380	1380	2808
N_b (10^{11} p/bunch)	1.2	1.45	1.6	1.15
ε (μm rad)	2.4	2.4	2.5	3.75
β^* (m)	3.5	1.5 $\rightarrow$ 1	0.6	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.5×10^{33}	7.6×10^{33}	10^{34}
average pile-up @ start of fill	8	17	38	26
stored energy (MJ)	25	112	140	362

The search for high-mass objects will be exciting with the much higher cross sections in the coming LHC run



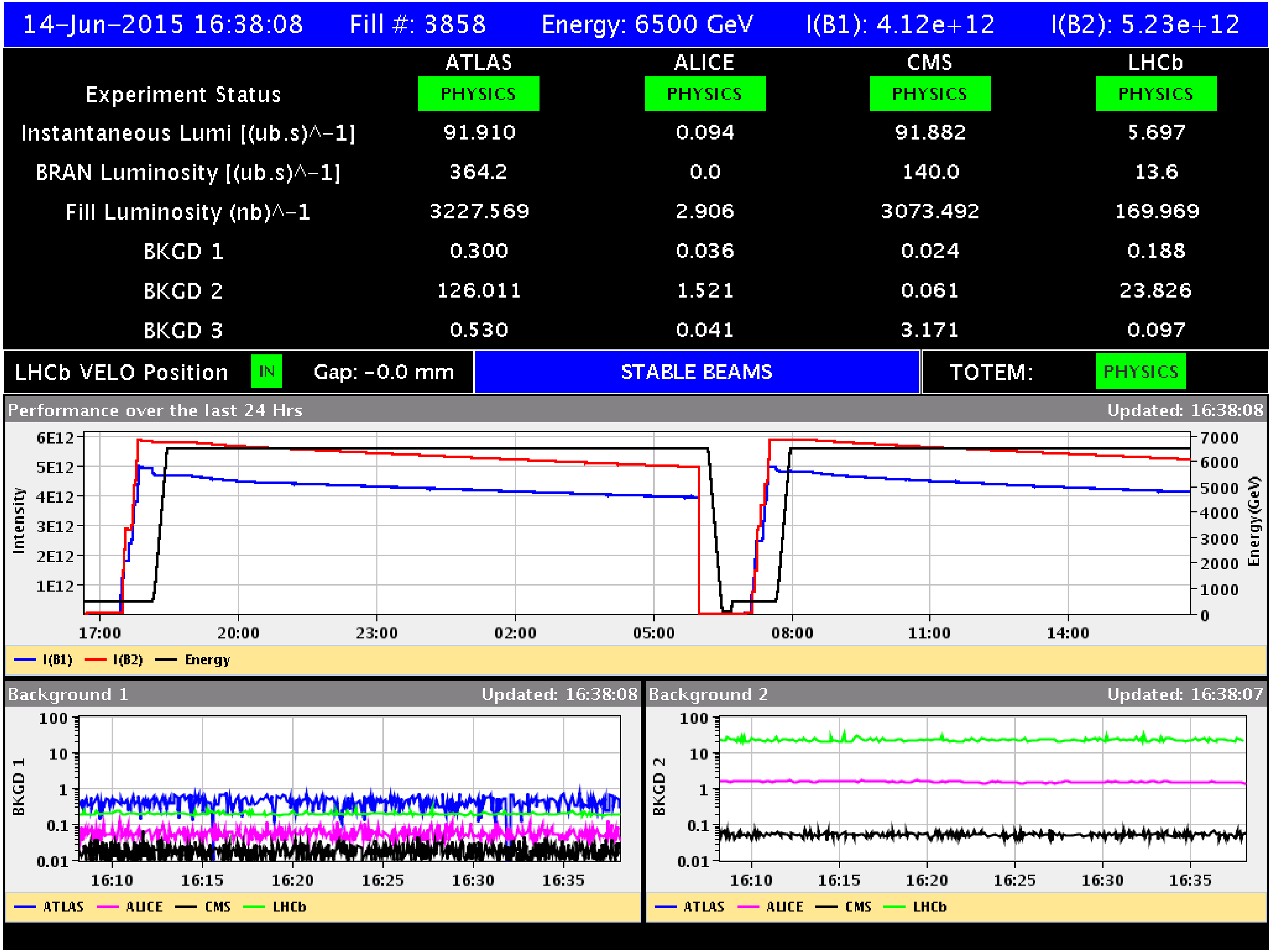


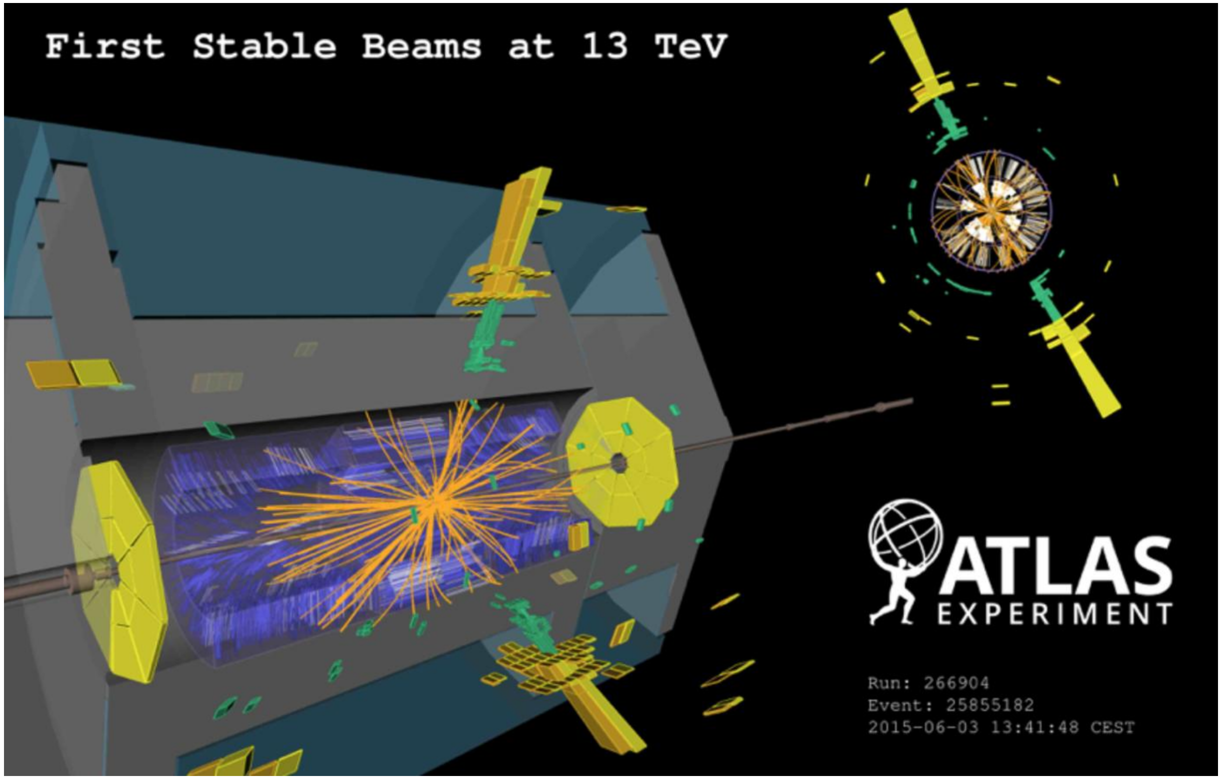
W J Stirling; many interesting plots can be found on his web:
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html


13 TeV / 8 TeV inclusive pp cross-section ratio
Minimum bias 1.2
W(ln) 1.6
Z(ll) 1.7
ZZ 2.0
t (s-channel) 2.2
t (t-channel) 2.5
WH 2.0
H (ggF) 2.3
H (VBF) 2.4
tt 3.3
ttZ 3.6
ttH 3.9
A(0.5 TeV, ggF+bbA) 4.0
stop pair (0.7 TeV) 8.4
gluino pair (1.5 TeV) 46
Z' SSM (3 TeV) 10
Q* (4 Tev) 56
QBH (5 TeV) 370
QBH (6 TeV) 9000
1
10
100
1000
10000

6.5 TeV for the first time !

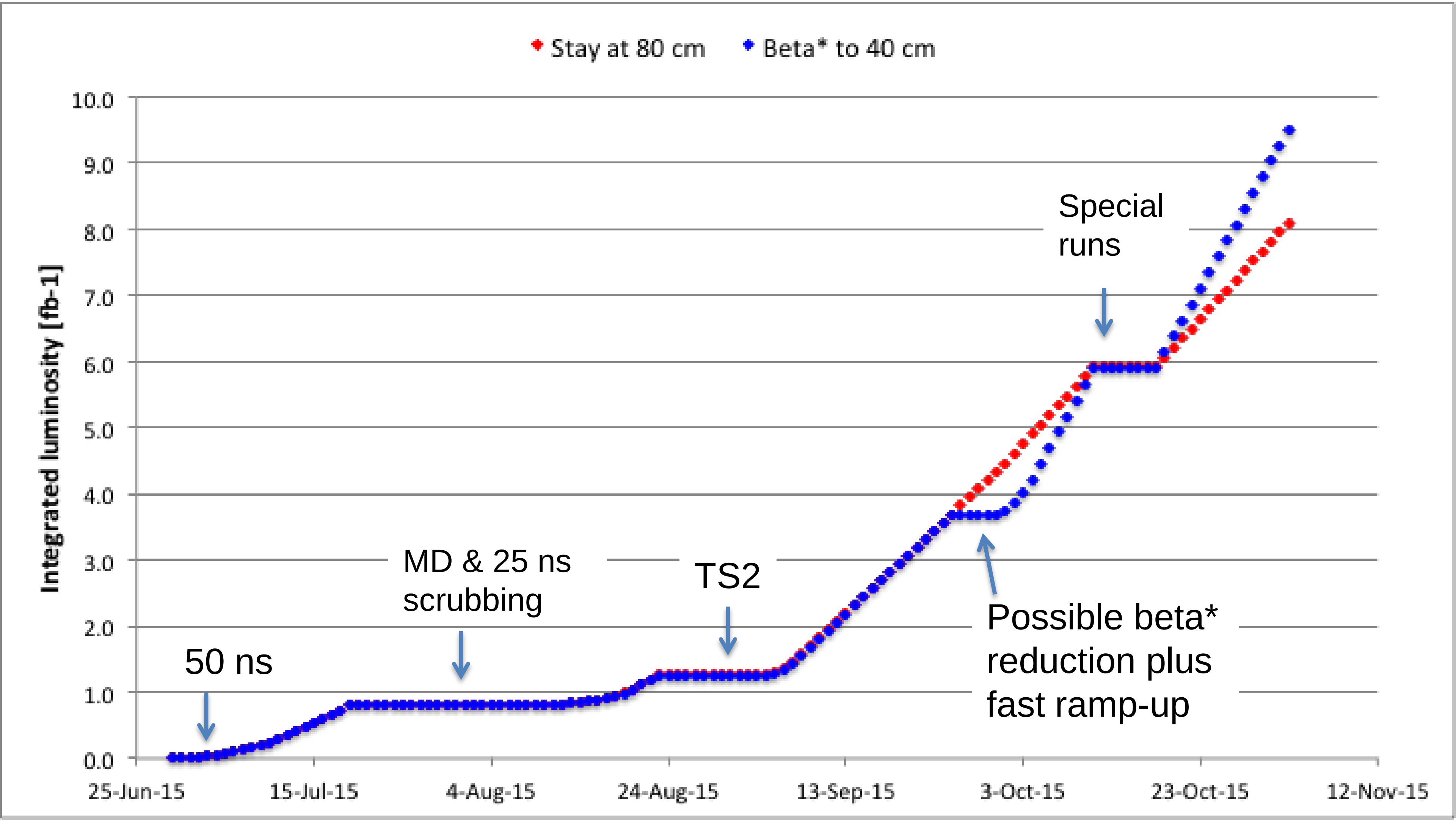
01:03 10th April 2015


14-Jun-2015 16:38:08
Fill #: 3858
Energy: 6500 GeV
I(B1): 4.12e+12
I(B2): 5.23e+12
ATLAS
ALICE
CMS
LHCb
Experiment Status
PHYSICS
PHYSICS
PHYSICS
PHYSICS
Instantaneous Lumi [(ub.s)^-1] 91.910 0.094 91.882 5.697
BRAN Luminosity [(ub.s)^-1] 364.2 0.0 140.0 13.6
Fill Luminosity (nb)^-1 3227.569 2.906 3073.492 169.969
BKGD 1 0.300 0.036 0.024 0.188
BKGD 2 126.011 1.521 0.061 23.826
BKGD 3 0.530 0.041 3.171 0.097
LHCb VELO Position
IN
Gap: -0.0 mm
STABLE BEAMS
TOTEM:
PHYSICS
Performance over the last 24 Hrs
Updated: 16:38:08
Intensity
Energy(GeV)
I(B1)
I(B2)
Energy
Background 1
Updated: 16:38:08
BKGD 1
Background 2
Updated: 16:38:07
BKGD 2
ATLAS
ALICE
CMS
LHCb

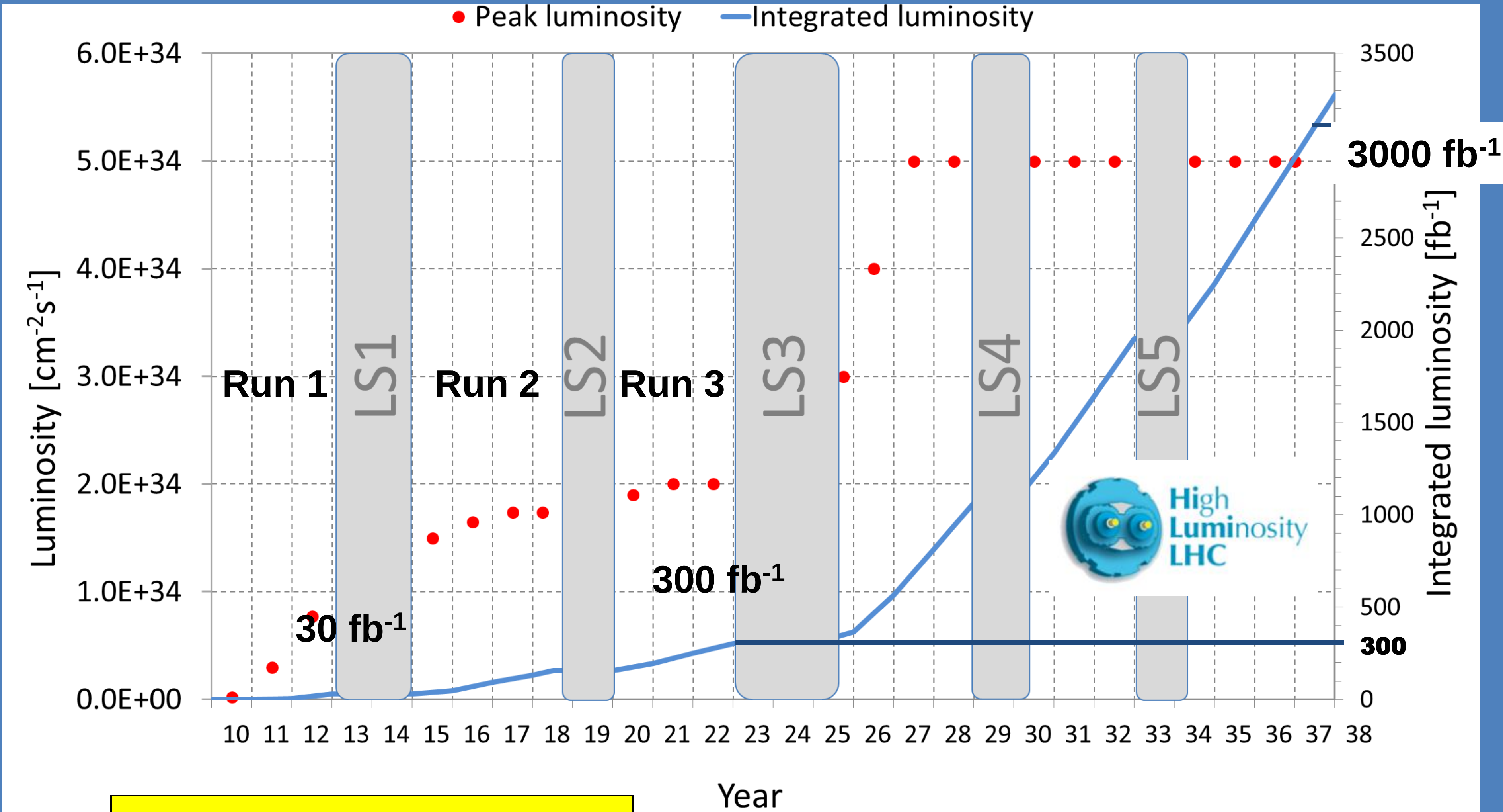

First Stable Beams at 13 TeV
ATLAS
EXPERIMENT
Run: 266904
Event: 25855182
2015-06-03 13:41:48 CEST

2015 LHC pp luminosity expectations

(Mike Lamont 15 June 2015)



LHC roadmap: Goal of 3'000 fb^{-1} by mid 2030s

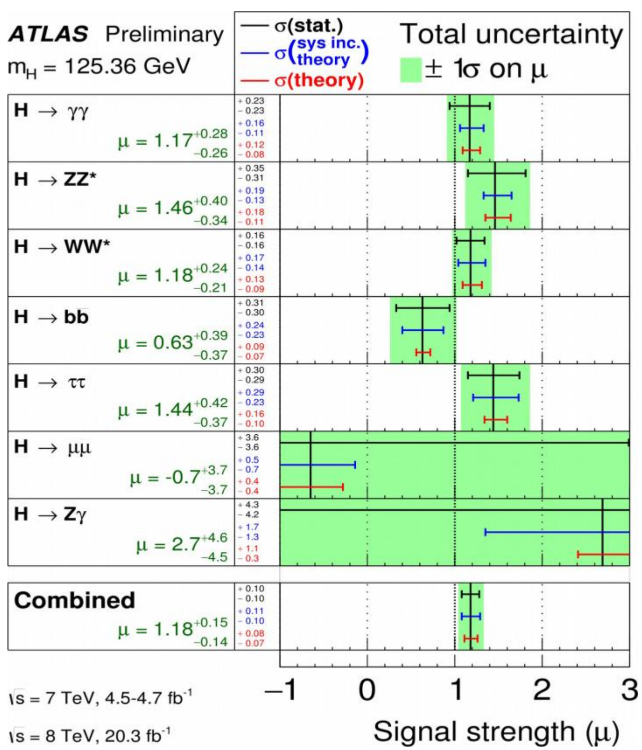


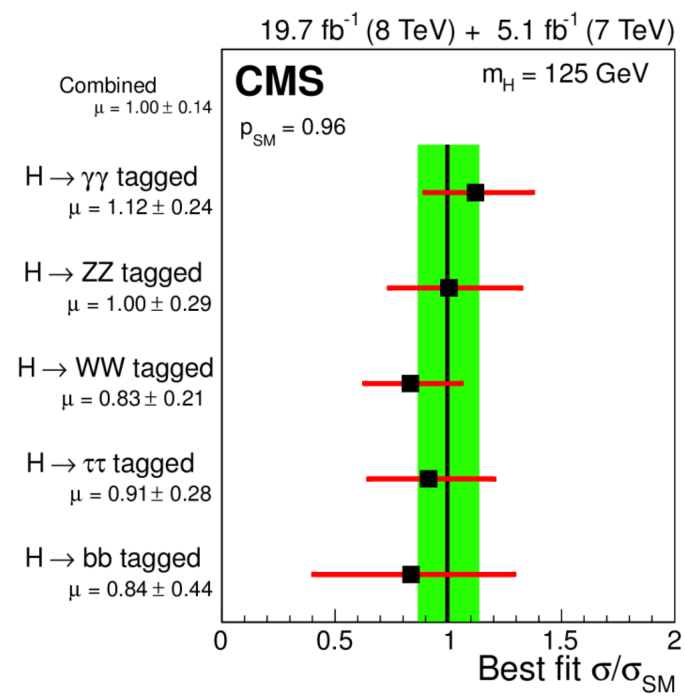
F Bordry, FCC WS March 2015

High Luminosity project (HL-LHC)

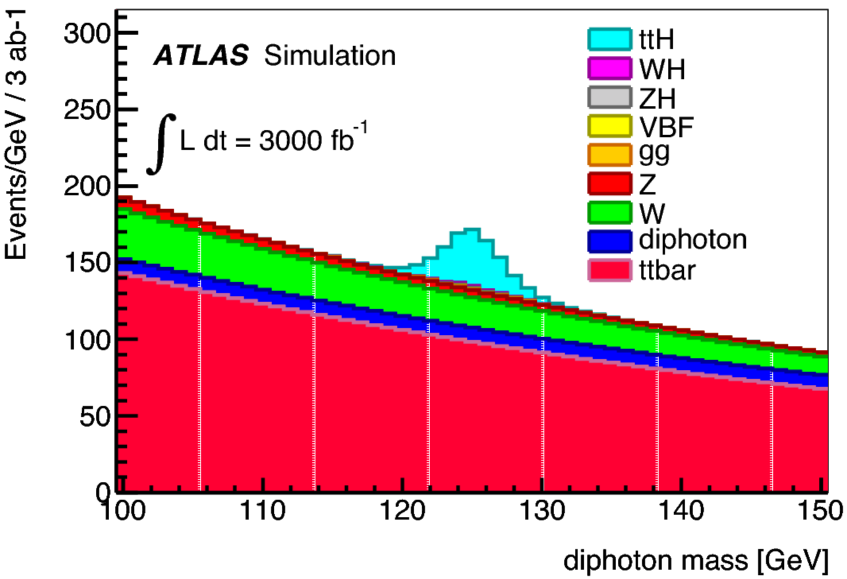
Complementary technologies providing comparable performances in term of significance of the signals !

Experiment	ATLAS		CMS	
Decay mode/combination	Expected (σ)	Observed (σ)	Expected (σ)	Observed (σ)
γγ	4.6	5.2	5.3	5.6
ZZ	6.2	8.1	6.3	6.5
WW	5.8	6.1	5.4	4.7
bb	2.6	1.4	2.6	2.0
ττ	3.4	4.5	3.9	3.8



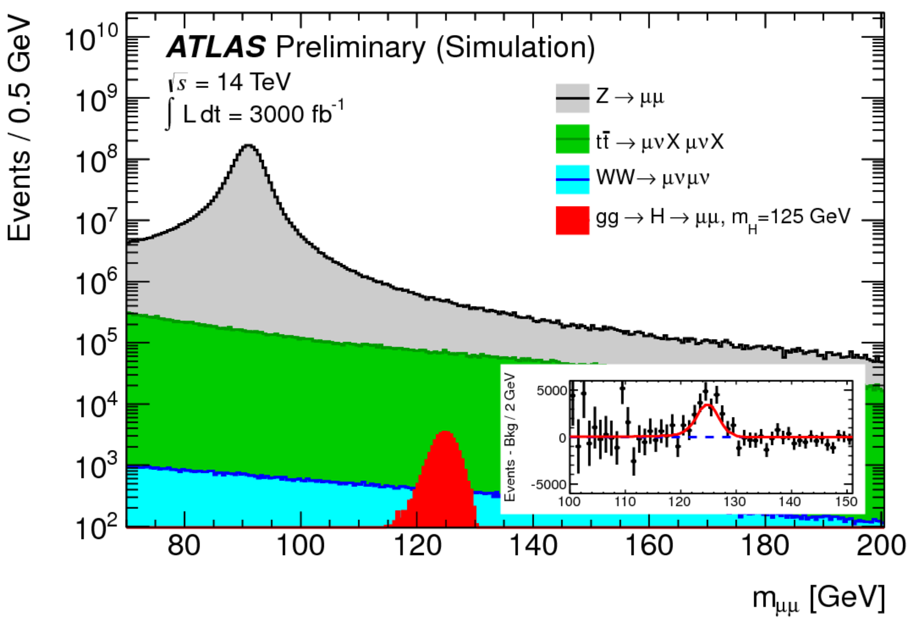


Outlook for HL-LHC on the Higgs physics



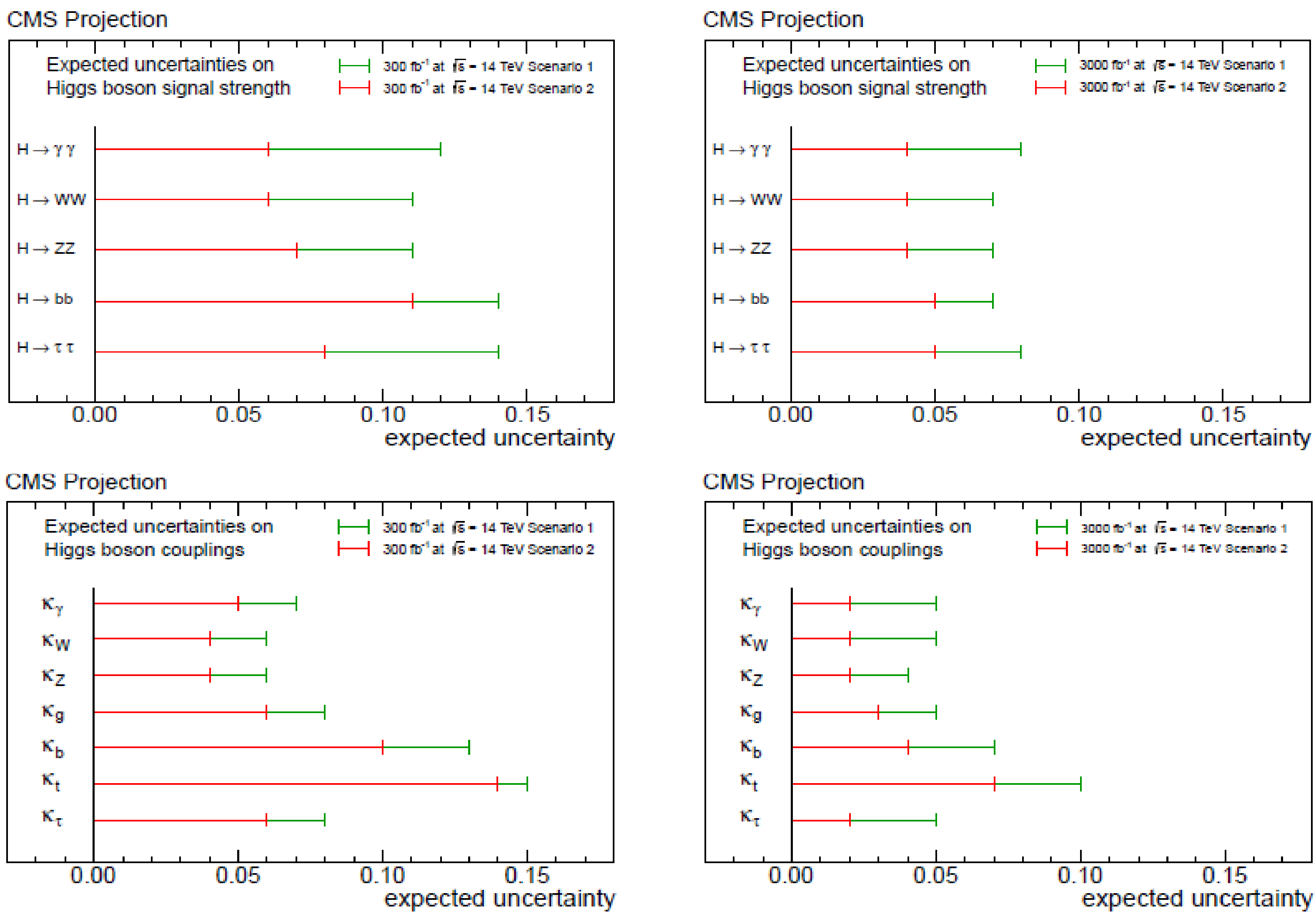
ttH with H → γγ for 3000 fb^{-1}

H → μμ for 3000 fb^{-1}



ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

Outlook for HL-LHC on the Higgs physics



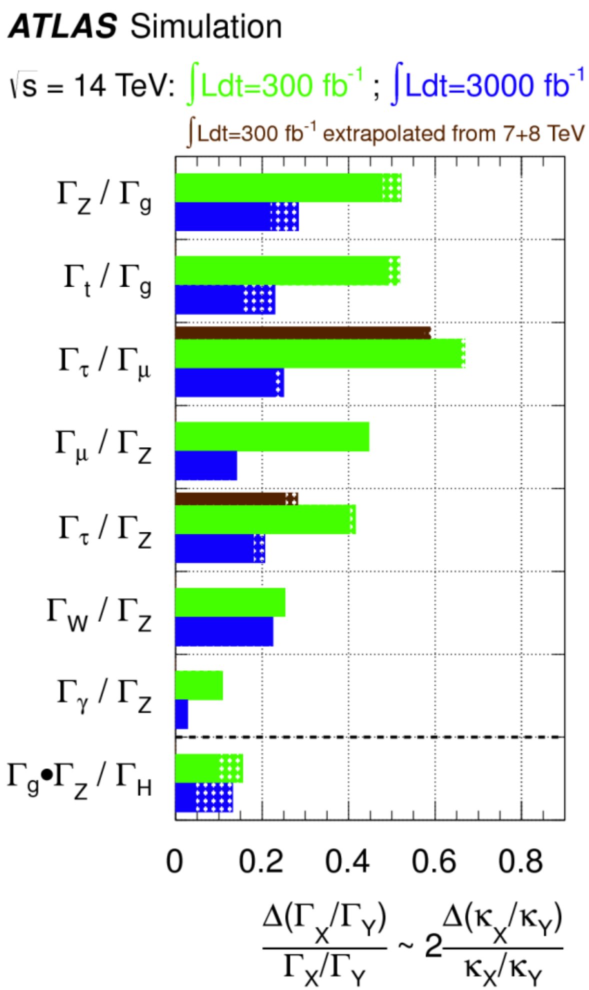
CMS NOTE-13-002, arXiv:1307.7135 [hep-ex]

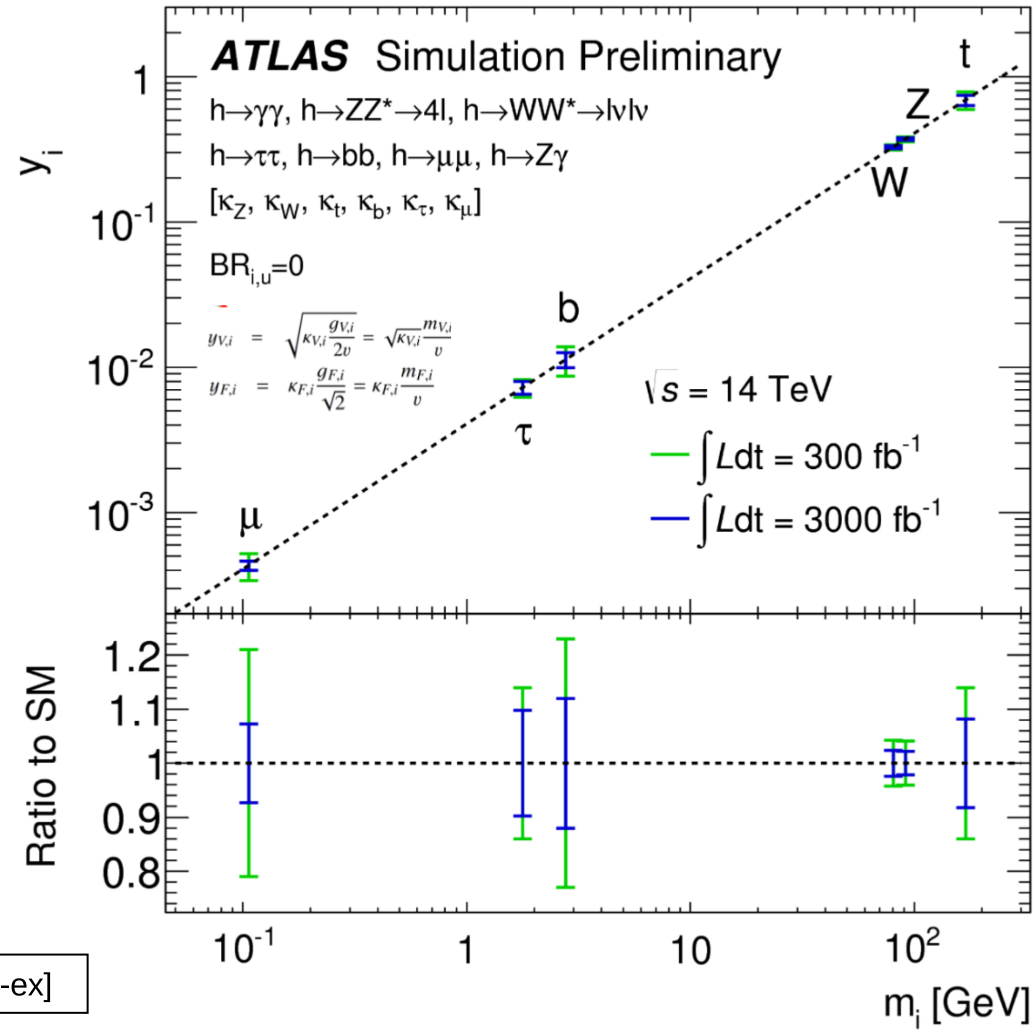
CMS considers two extrapolation scenarios:

Scenario 1: systematic errors are left unchanged

Scenario 2: theoretical errors scaled by 0.5, other syst. errors scaled by √luminosity

Outlook for HL-LHC on the Higgs physics

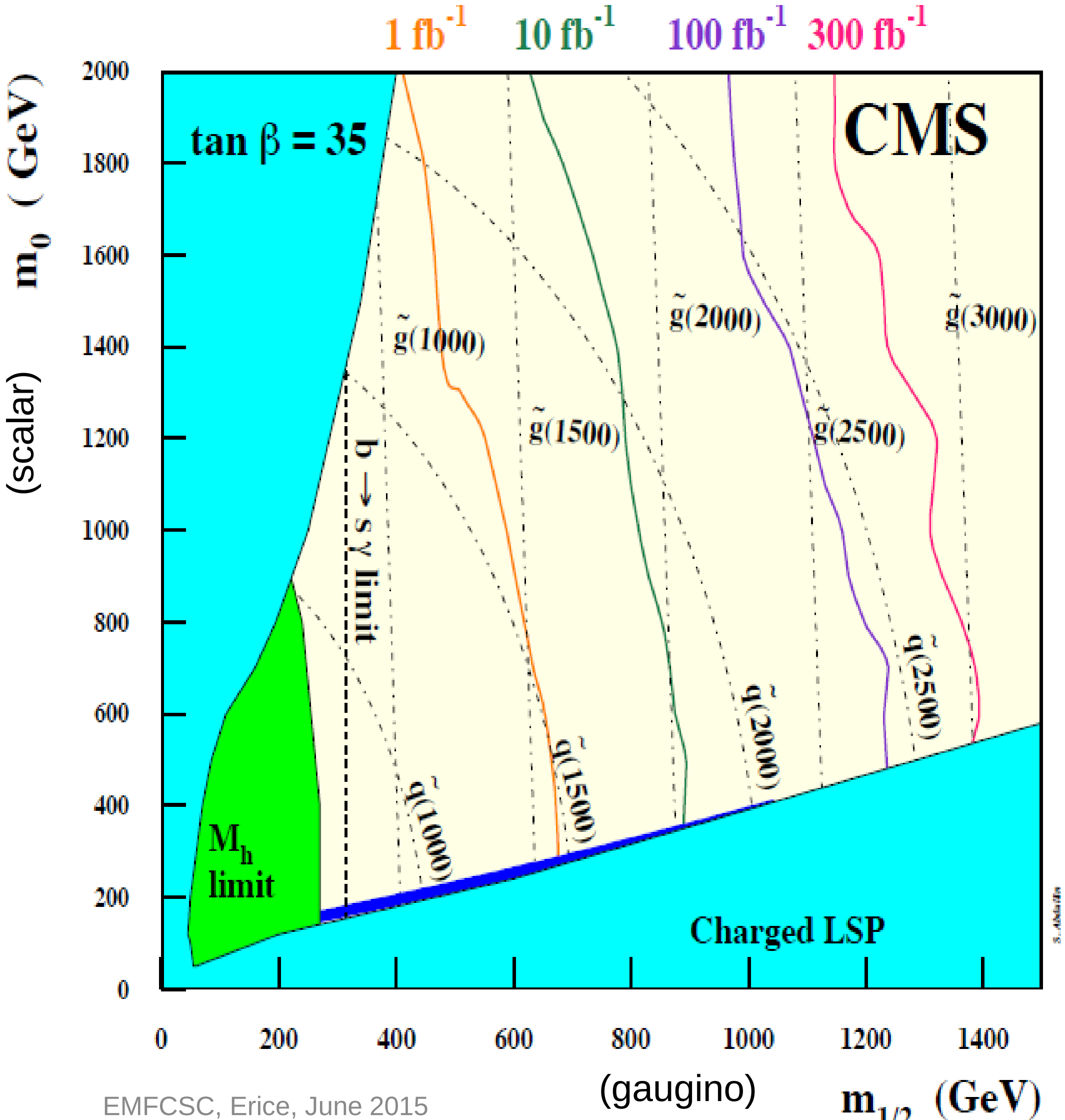


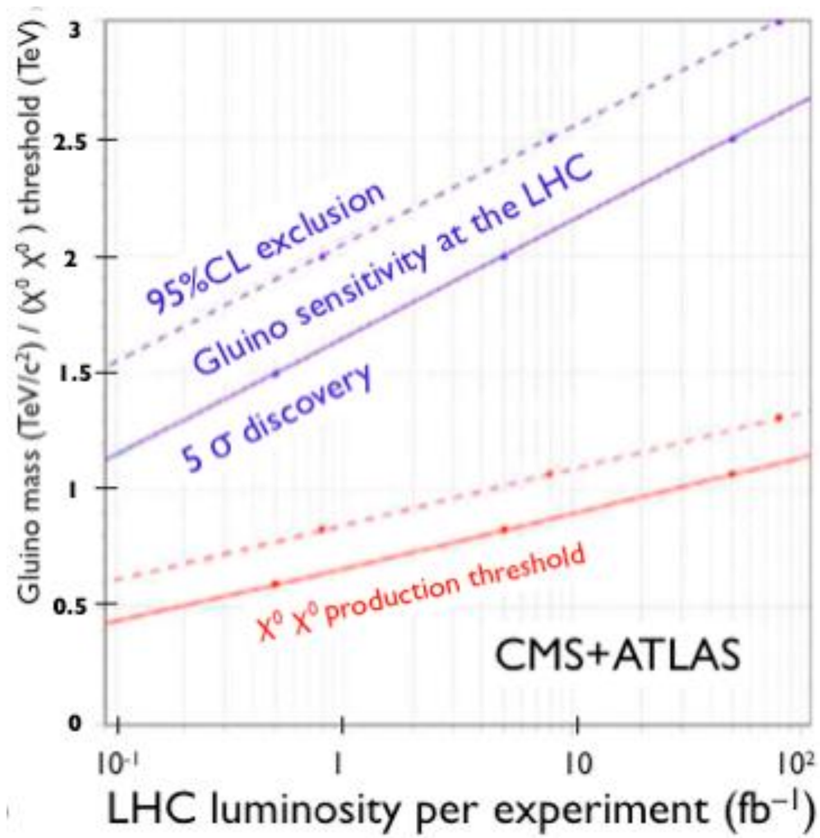


ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

Ultimate discovery reach for SUSY particles at the LHC (indicative plots, model-dependent…)

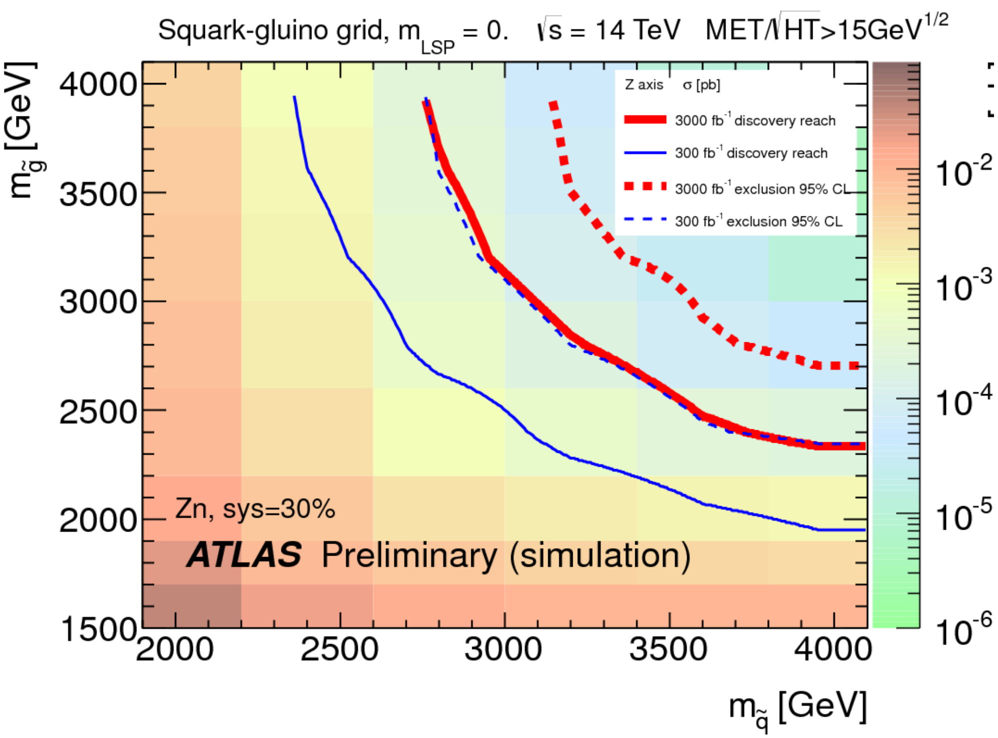
An old slide from well before the LHC start-up

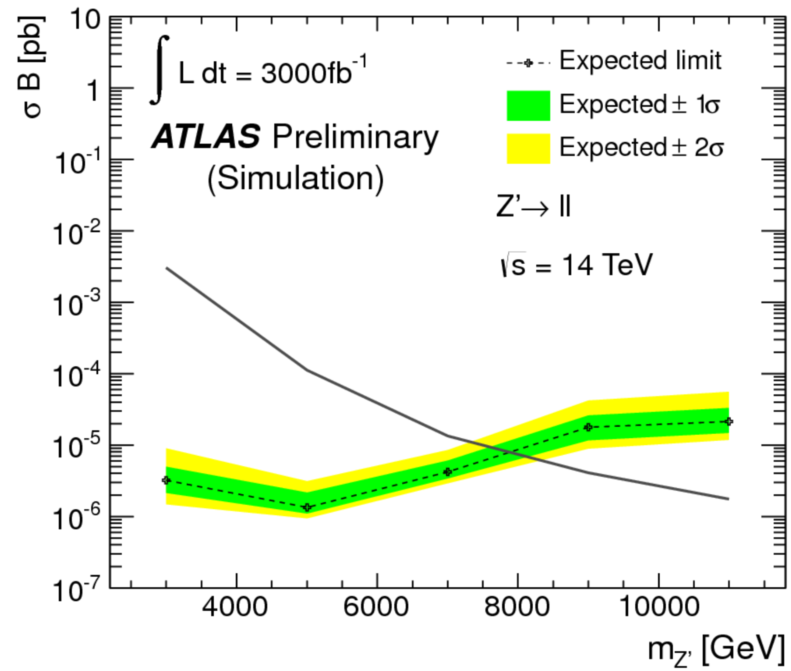




The mass scale probed for squarks and gluinos will be typically 2.5 TeV by 2017

Examples of SUSY and Z′ mass reaches at HL-LHC



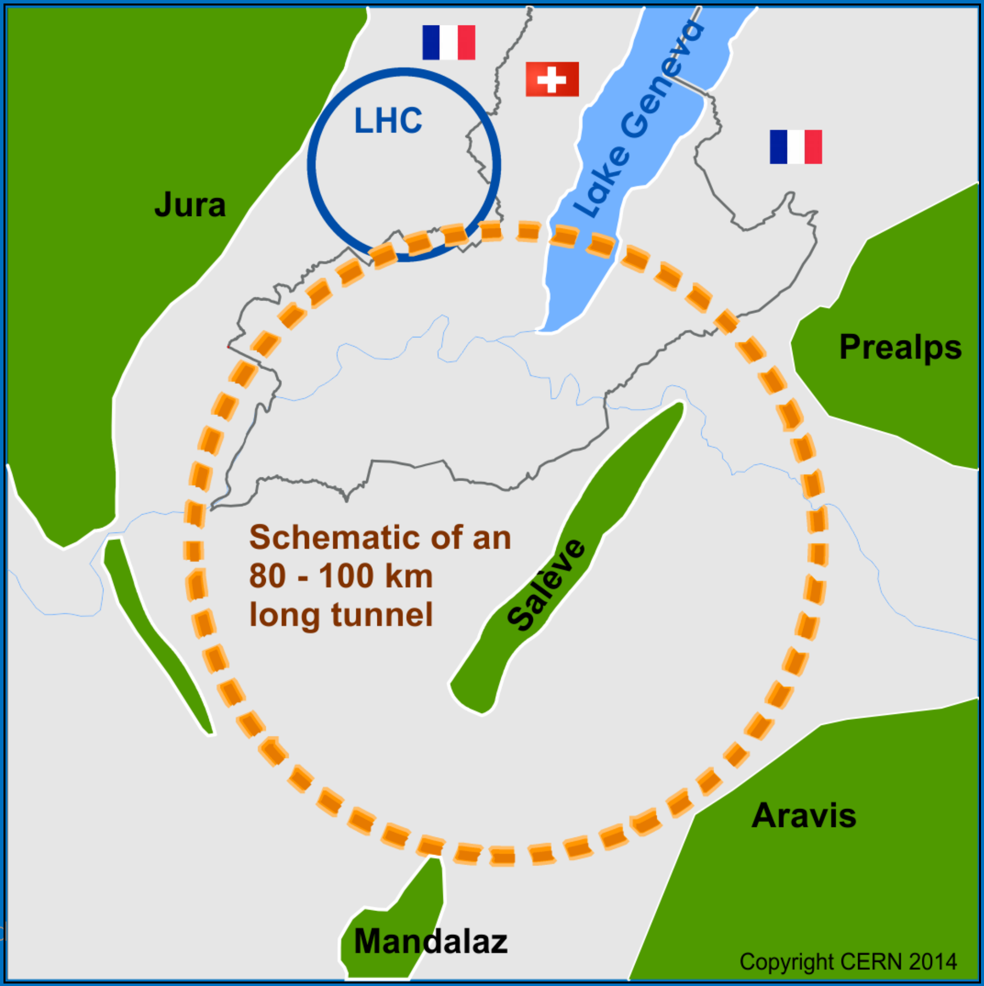


ATL-PHYS-PUB-2013-007, arXiv:1307.7292[hep-ex]

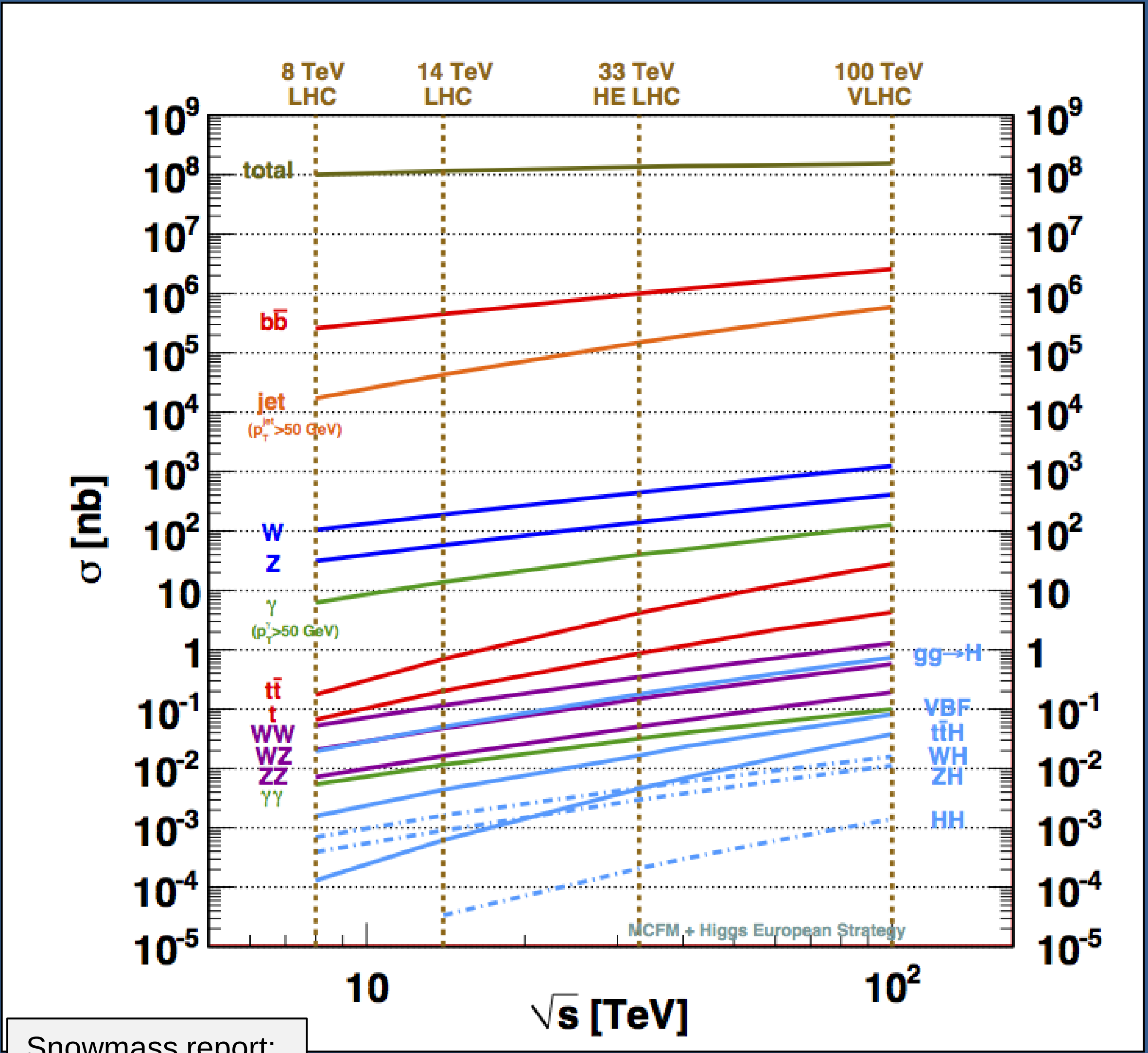
A very exciting dream for a facility in Europe:

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

For a Very High Energy Hadron Collider ranging from 42 TeV (8.3T LHC magnets) to 100 TeV (20T very high field magnets with HTS), and could house first an e^+e^- collider up to 350 GeV



Cross sections vs √s



Snowmass report: arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~ 7
Z	~ 7
WW	~ 10
ZZ	~ 10
tt	~ 30
H	~ 15 (ttH ~ 60)
HH	~ 40
stop (m=1 TeV)	~ 10^3

(F Gianotti)

Time line of the LHC project

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.
1987	Workshop on Physics at Future Accelerators, La Thuile, Italy. The Rubbia "Long-Range Planning Committee" recommends the Large Hadron Collider as the right choice for CERN's future.
1990	European Committee for Future Accelerators (ECFA) LHC Workshop, Aachen (discussion of physics, technologies and designs for LHC experiments)
1992	General Meeting on LHC Physics and Detectors, Evian les Bains (4 general-purpose experiment designs presented along with their physics performance)
1993	Three Letters of Intent submitted to the CERN peer review committee LHCC. ATLAS and CMS selected to proceed to a detailed technical proposal.
1994	The LHC accelerator approved for construction
1996	ATLAS and CMS Technical Proposals approved.
1997	Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 MCHF)
1997	Construction commences (after approval of detailed engineering design of subdetectors (magnets, inner tracker, calorimeters, muon system, trigger and data acquisition))
2000	Assembly of experiments commences, LEP accelerator is closed down to make way for the LHC.
2008	LHC experiments ready for pp collisions. LHC starts operation. An incident stops LHC operation.
2009	LHC restarts operation, pp collisions recorded by LHC detectors
2010	LHC collides protons at high energy (centre of mass energy of 7 TeV)
2012	LHC operates at 8 TeV: discovery of a Higgs-like boson.

It took a long time, and we already had a tunnel…

Strategy toward physics

A slide from 2008, at the time of anticipating first collisions

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.)
  $\rightarrow$ test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \rightarrow ll$, …)
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

Prepare the road to discoveries …

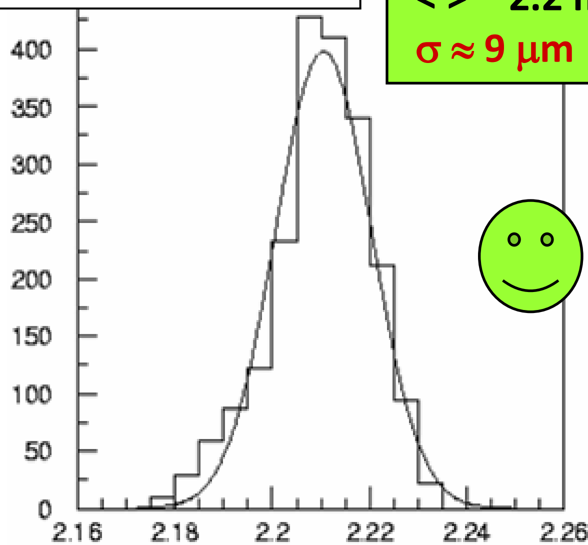
Construction example: ATLAS LAr em Accordion Calorimeter

Construction quality

Thickness of Pb plates must
be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm
σ ≈ 9 μm

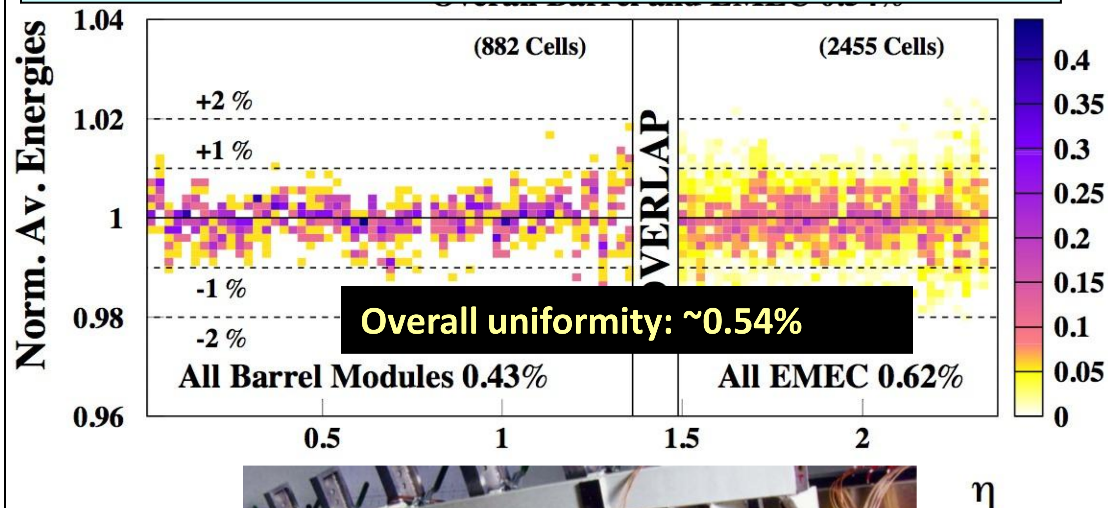


Absorber thickness (mm)

Test-beam measurements

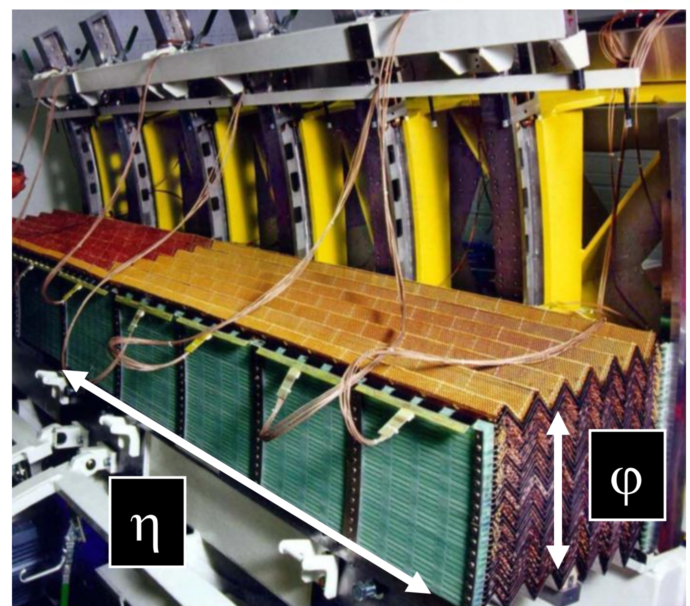
4 (out of 32) barrel modules and 3 (out of 16)
end-cap (EMEC) modules tested with beams

Scans with 120-245 GeV electrons (all 7 tested modules)



Overall uniformity: ~0.54%

1 barrel module:
$\Delta\eta \times \Delta\varphi = 1.4 \times 0.4$
≈ 3000 channels

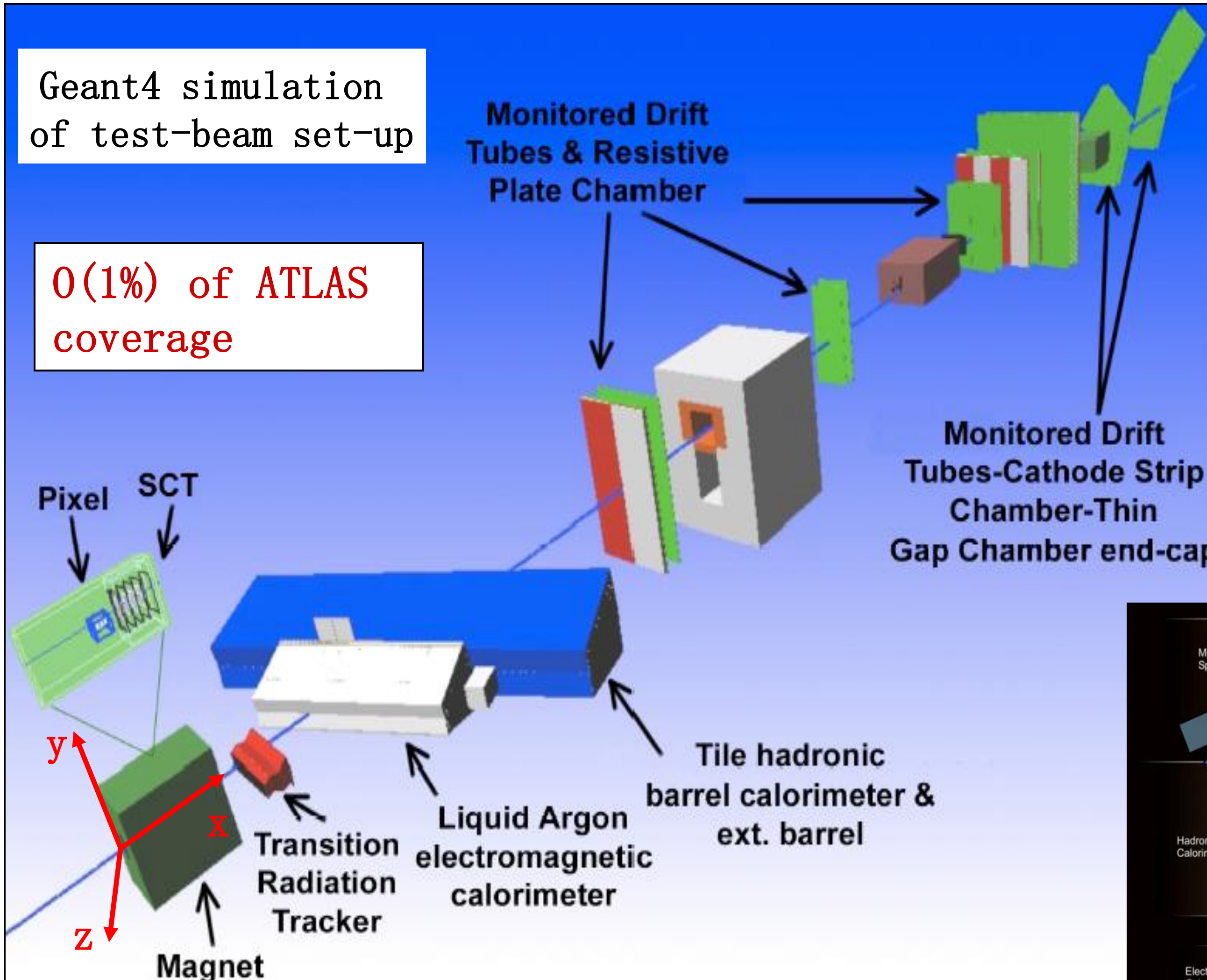


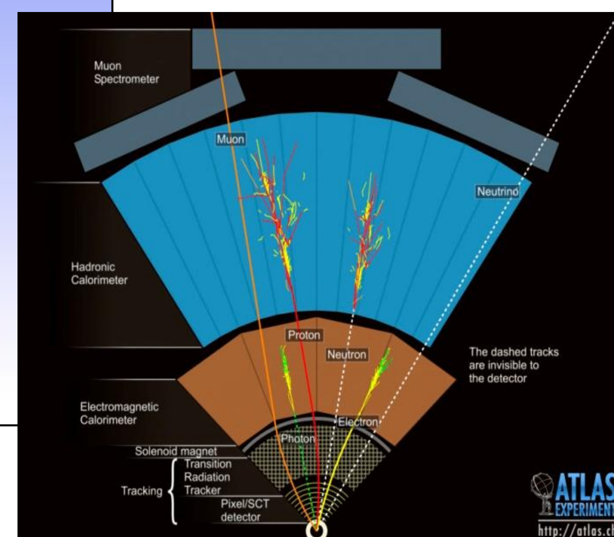
Example: 2004 ATLAS combined test beam

Full "vertical slice" of ATLAS tested in CERN H8 beam line

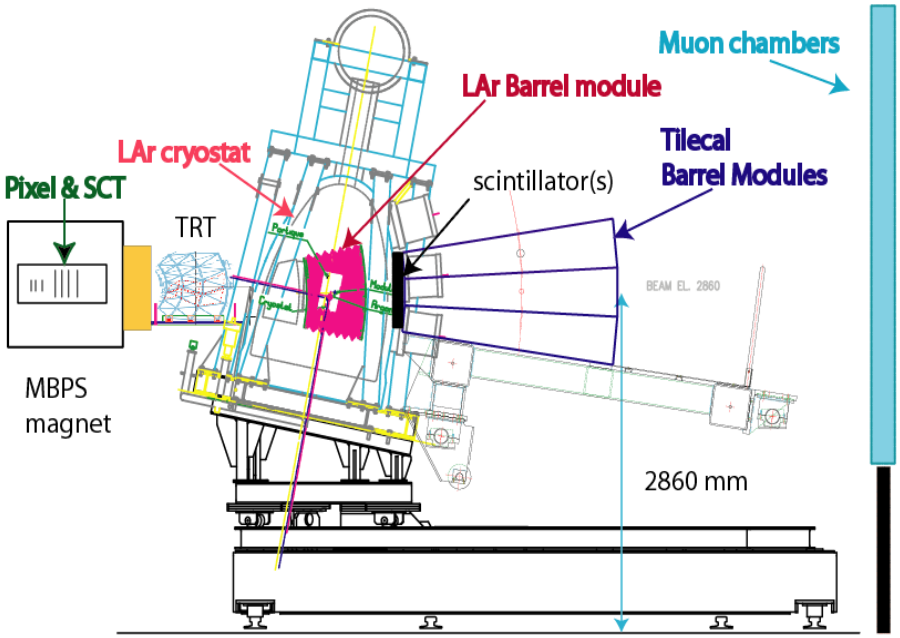
Geant4 simulation of test-beam set-up

O(1%) of ATLAS coverage



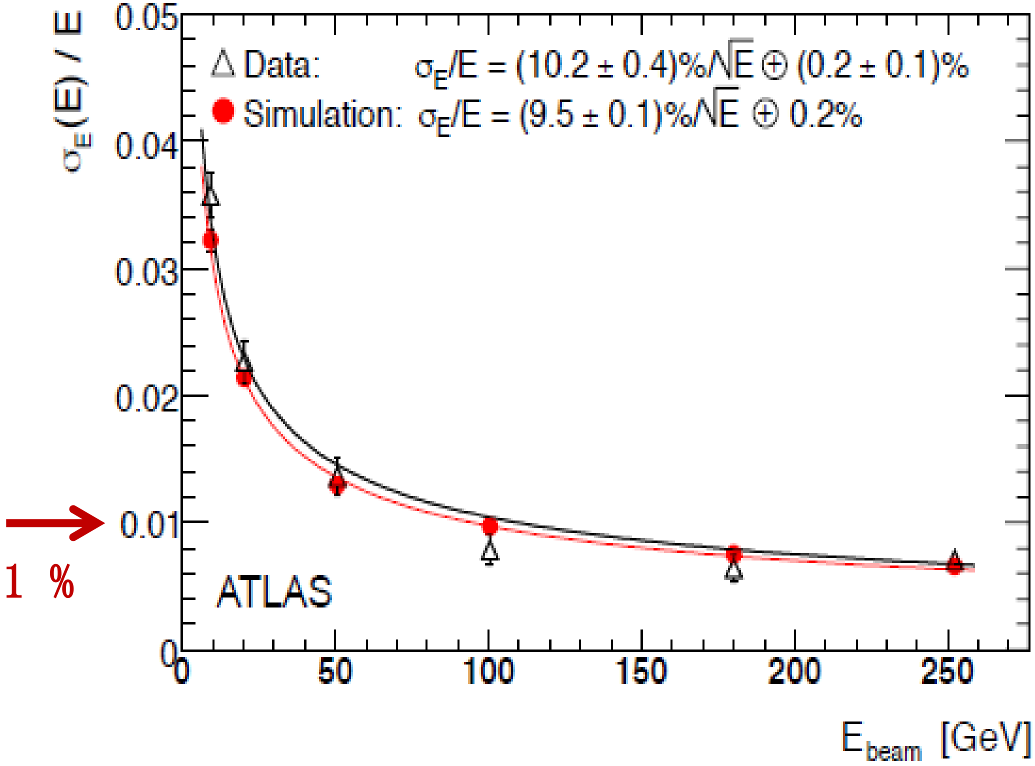


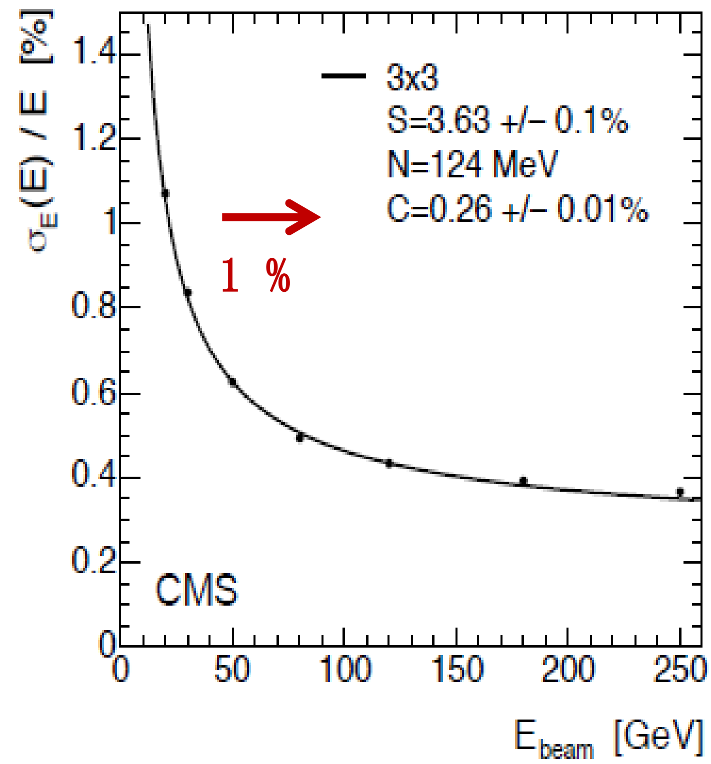
Combined test beam (H8 SPS)



All ATLAS sub-detectors (and LVL1 trigger) integrated and run together with common DAQ, monitoring, slow-control.
Data analyzed with common ATLAS software.
Gained lot of global operation experience during ~ 6 month run.

Examples of resolutions measured for electrons in ATLAS and CMS





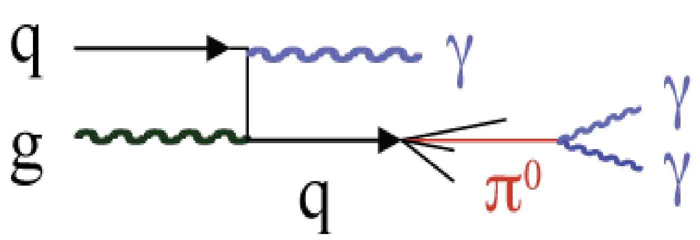
Need to be sure to identify electrons and photons

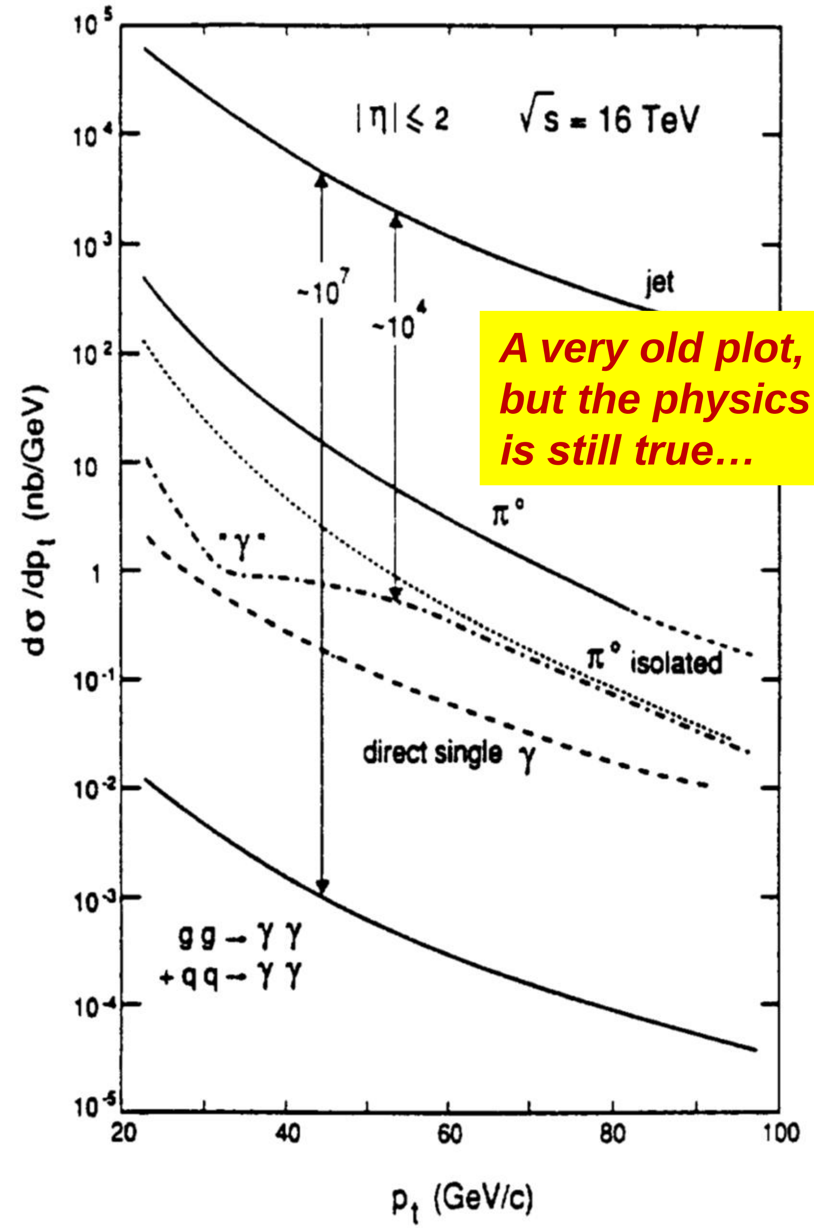
Most channels require to identify electrons and photons in their final states

At LHC the di-jets background dominates all high-p_T channels

Jet fragmentation into leading π_0 (probability 10^{-4}) represents the main source of identification errors

Example:

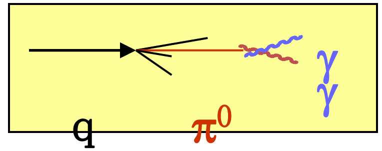




A very old plot, but the physics is still true…

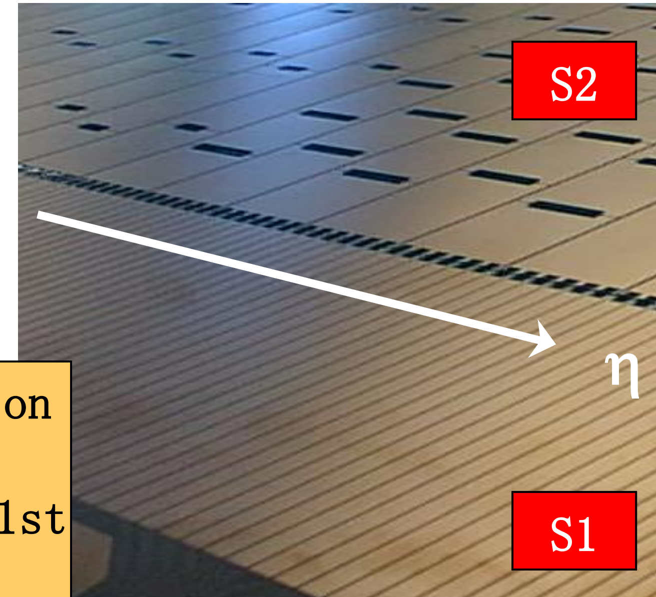
Photon identification

ATLAS

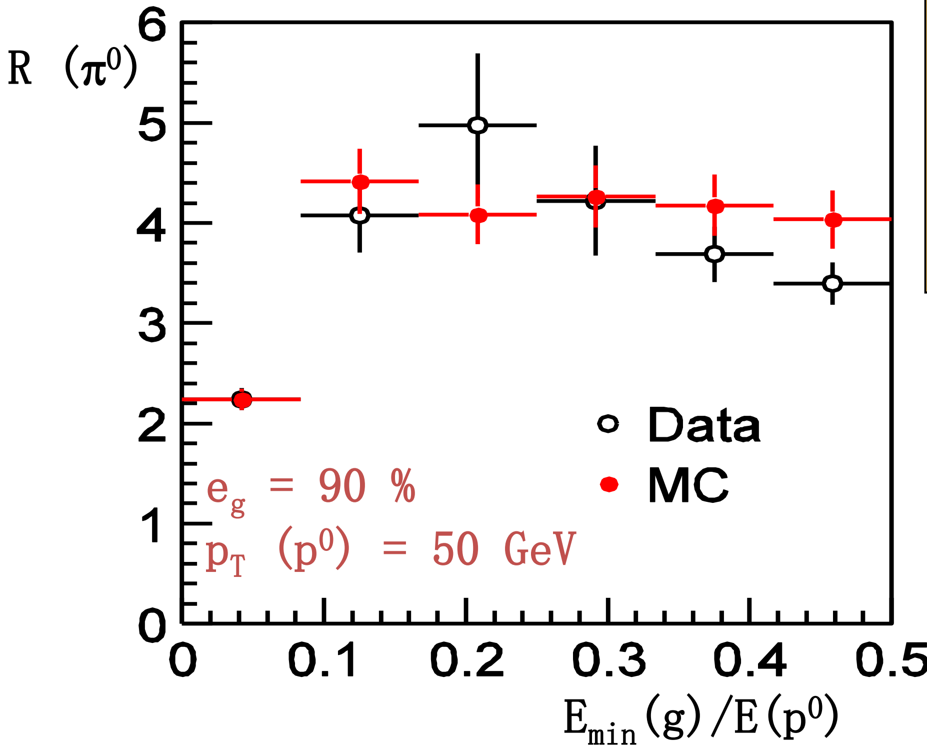


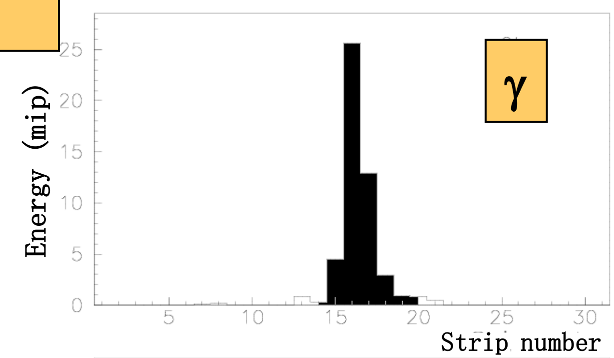
$R(\pi^0) \geq 3$ for $\varepsilon(\gamma)$ ~ 90% needed to reject γj+jj background to H →

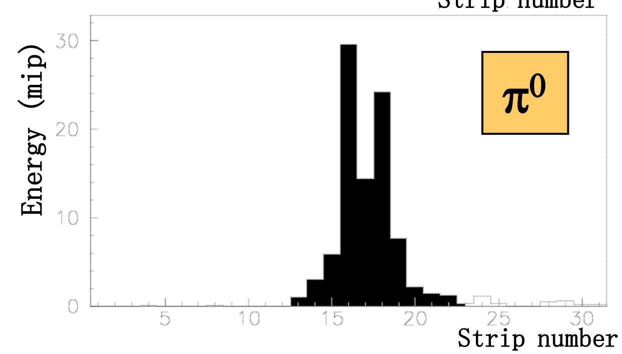
1999-2000 test-beam data collected with special photon beam



γ/π^0 separation based on 4mm η-strips in 1st calorimeter compartment







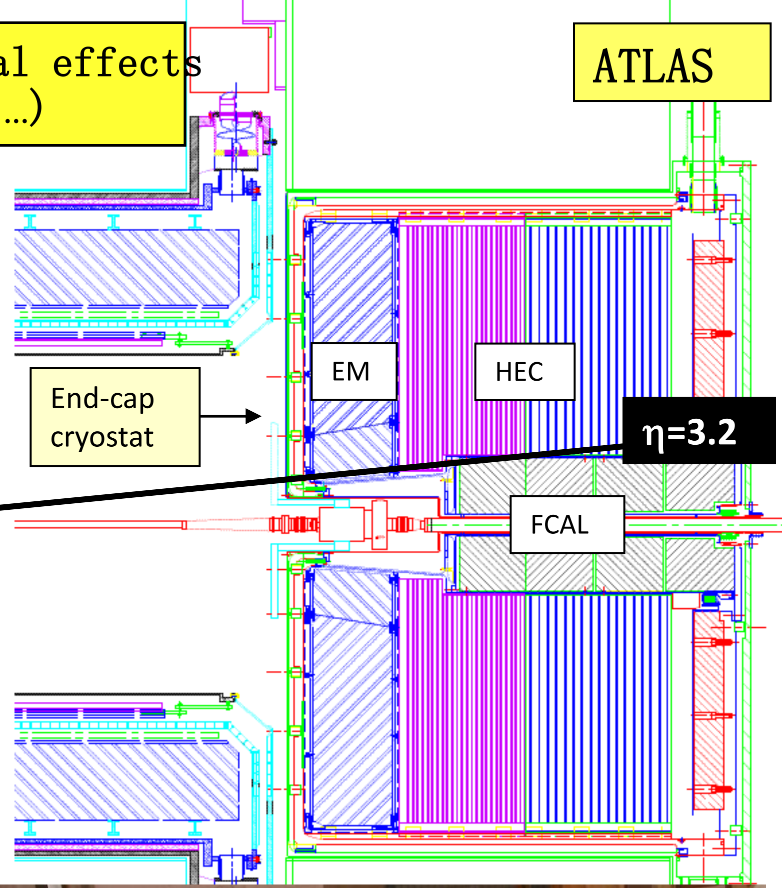
Data: $\langle R(\pi^0)\rangle = 3.54 \pm 0.12$

MC: $\langle R(\pi^0)\rangle = 3.66 \pm 0.10$

Background study: fake E_T^{miss} tails from instrumental effects (calorimeter non-compensation, resolution, cracks, …)

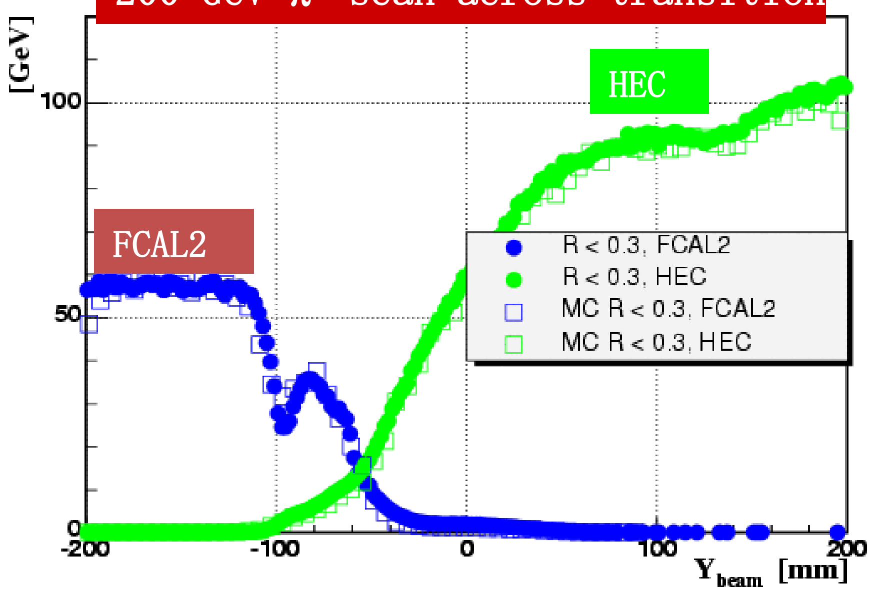
ATLAS

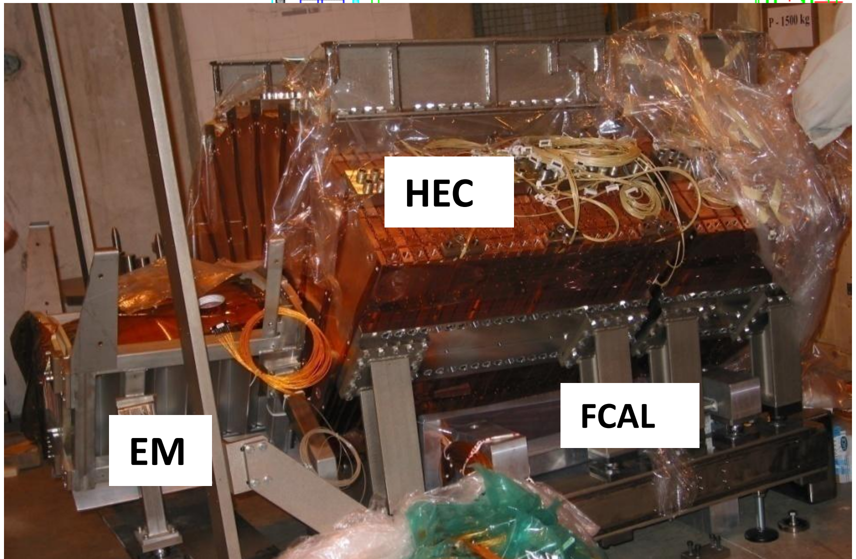
Transition between end-cap (EM, hadronic/HEC) and forward (FCAL) calorimeters at η=3.2 studied with dedicated combined test-beam in H6 beam in 2004

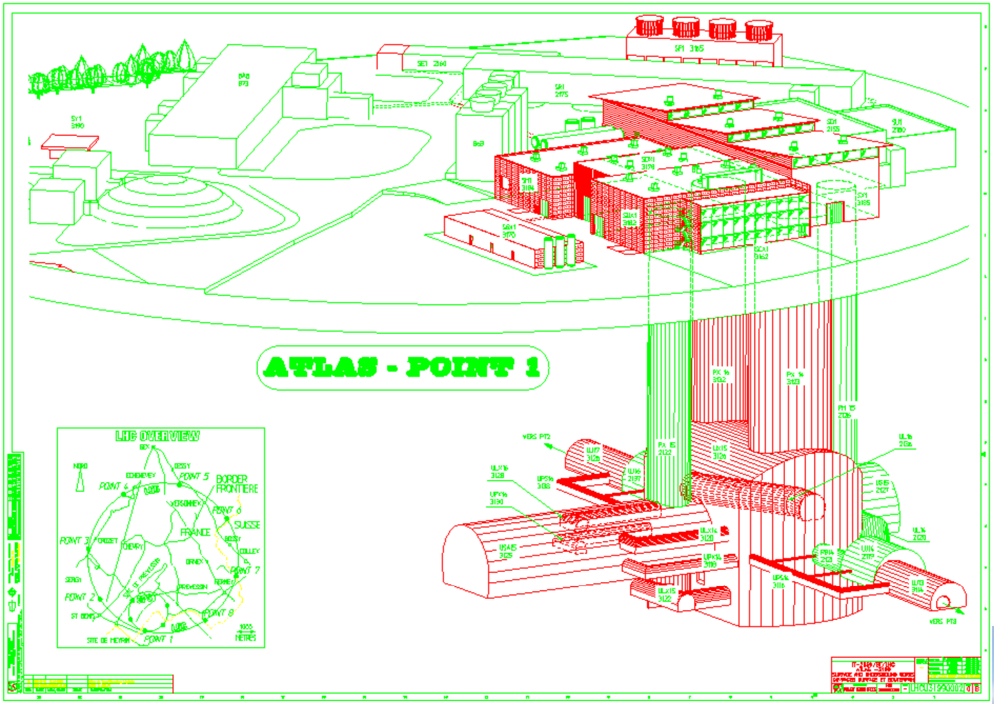


Data described well by MC in complex region with 3 different calorimeters and a lot of material

200 GeV π^- scan across transition

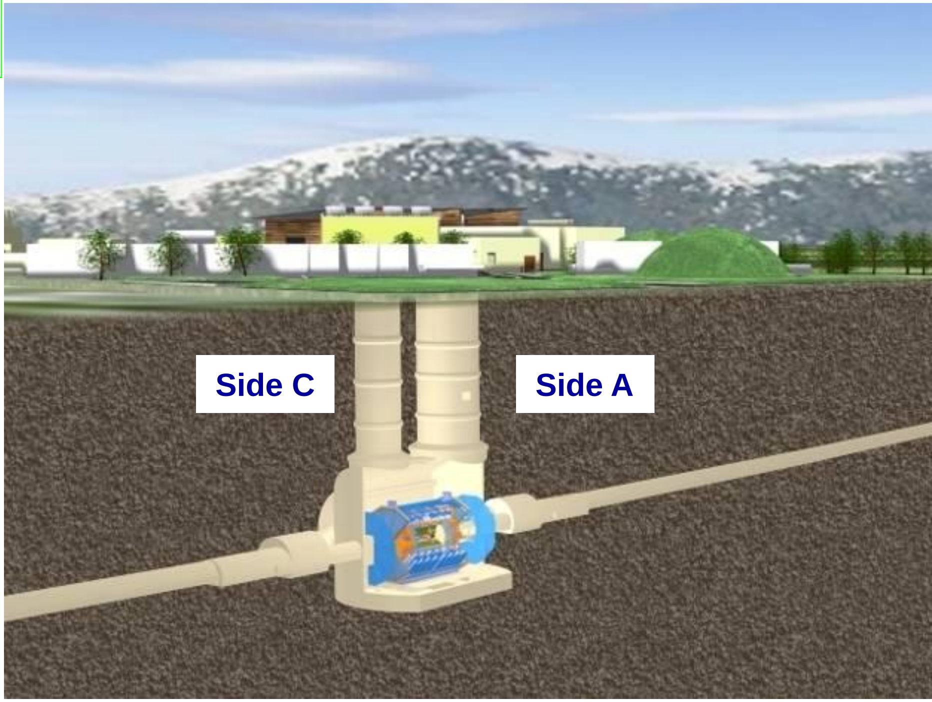






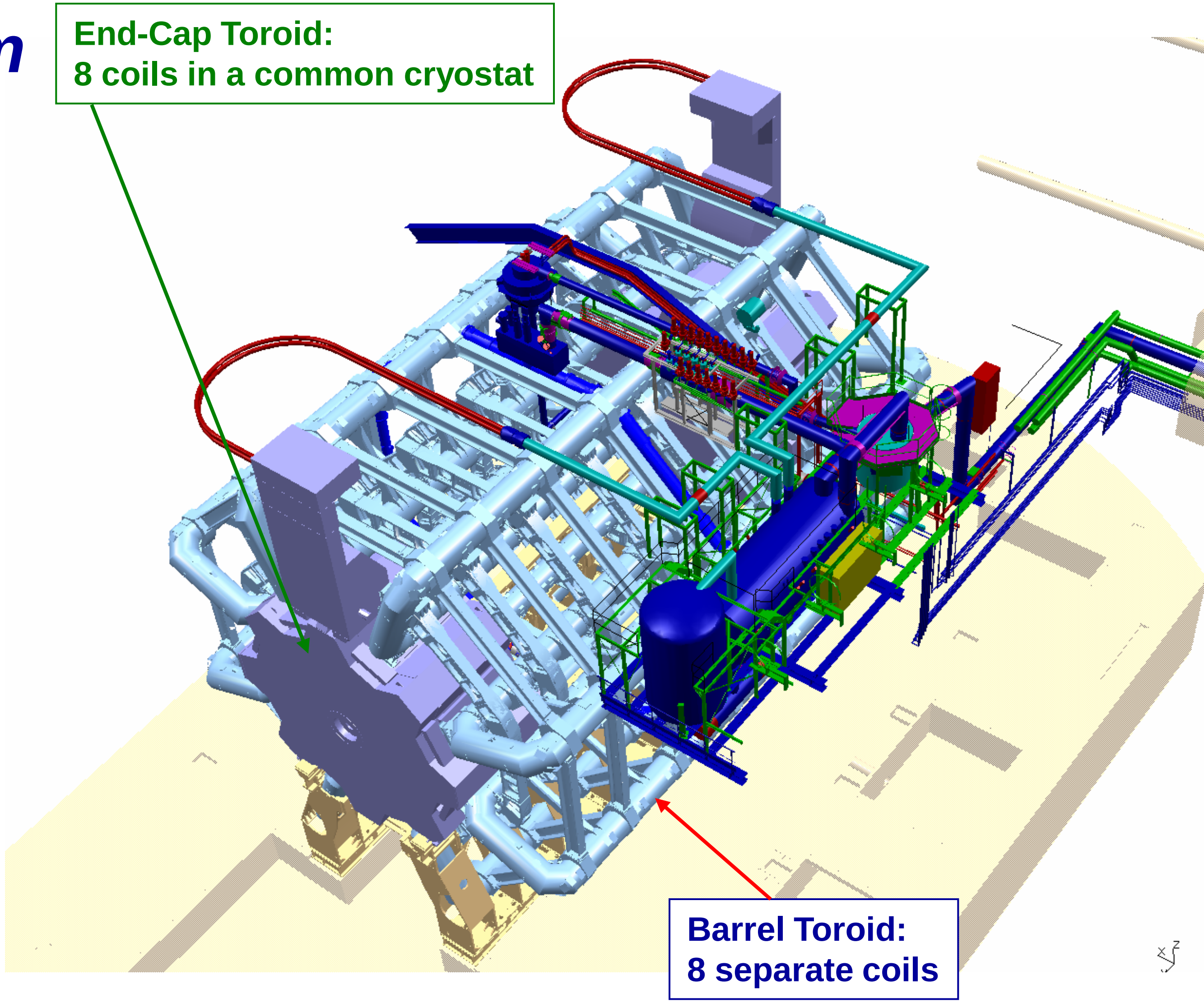
The Underground Cavern at Point-1 for the ATLAS Detector
(excavation started in 1998)

Length = 55 m
Width = 32 m
Height = 35 m



LHC Point 1 - UX 15 Cavern - Concrete walls 6th lift - 20-02-2003 - CERN ST-CE

ATLAS Toroid Magnet System



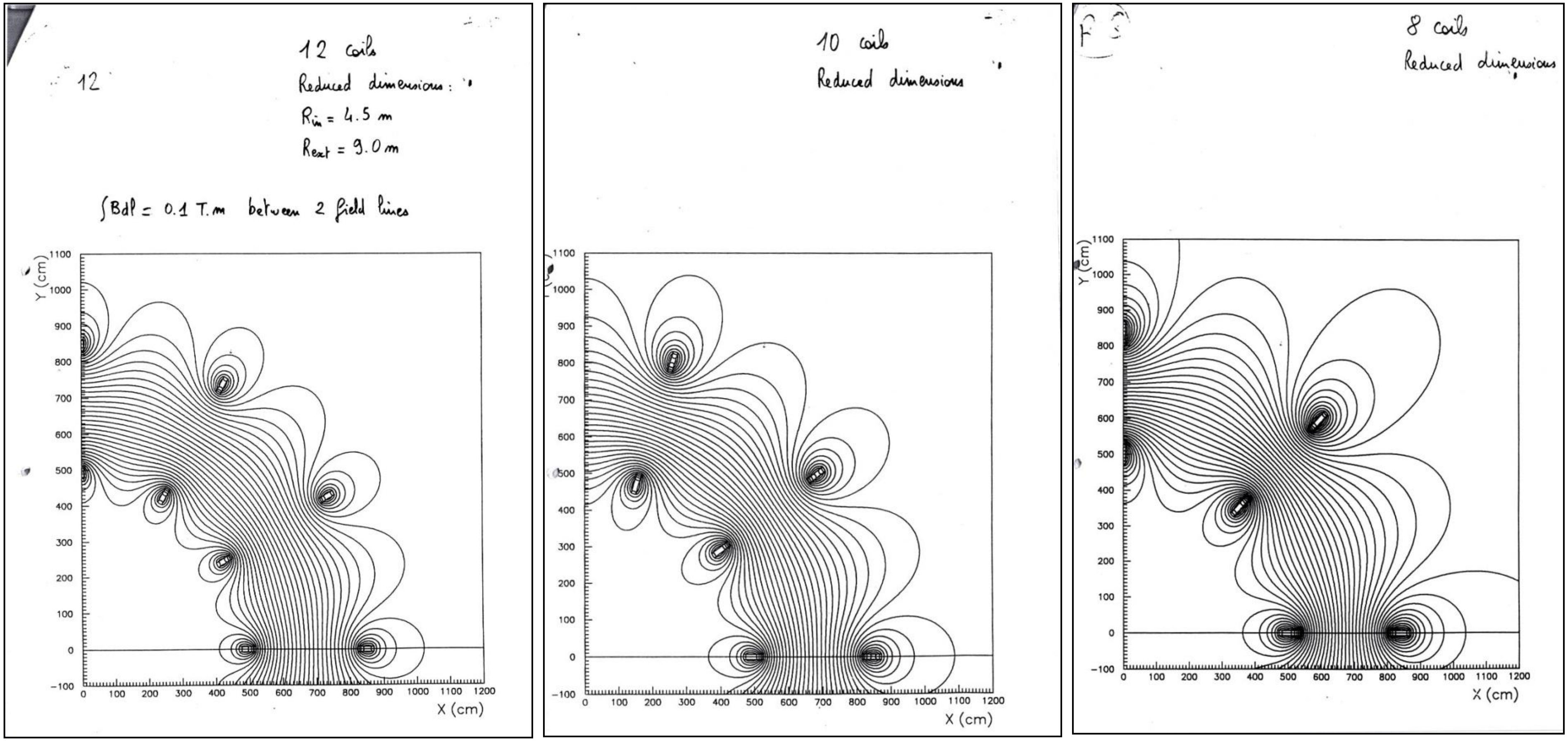
Barrel Toroid parameters

25.3 m length
20.1 m outer diameter
8 coils
1.08 GJ stored energy
370 tons cold mass
830 tons weight
4 T on superconductor
56 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

End-Cap Toroid parameters

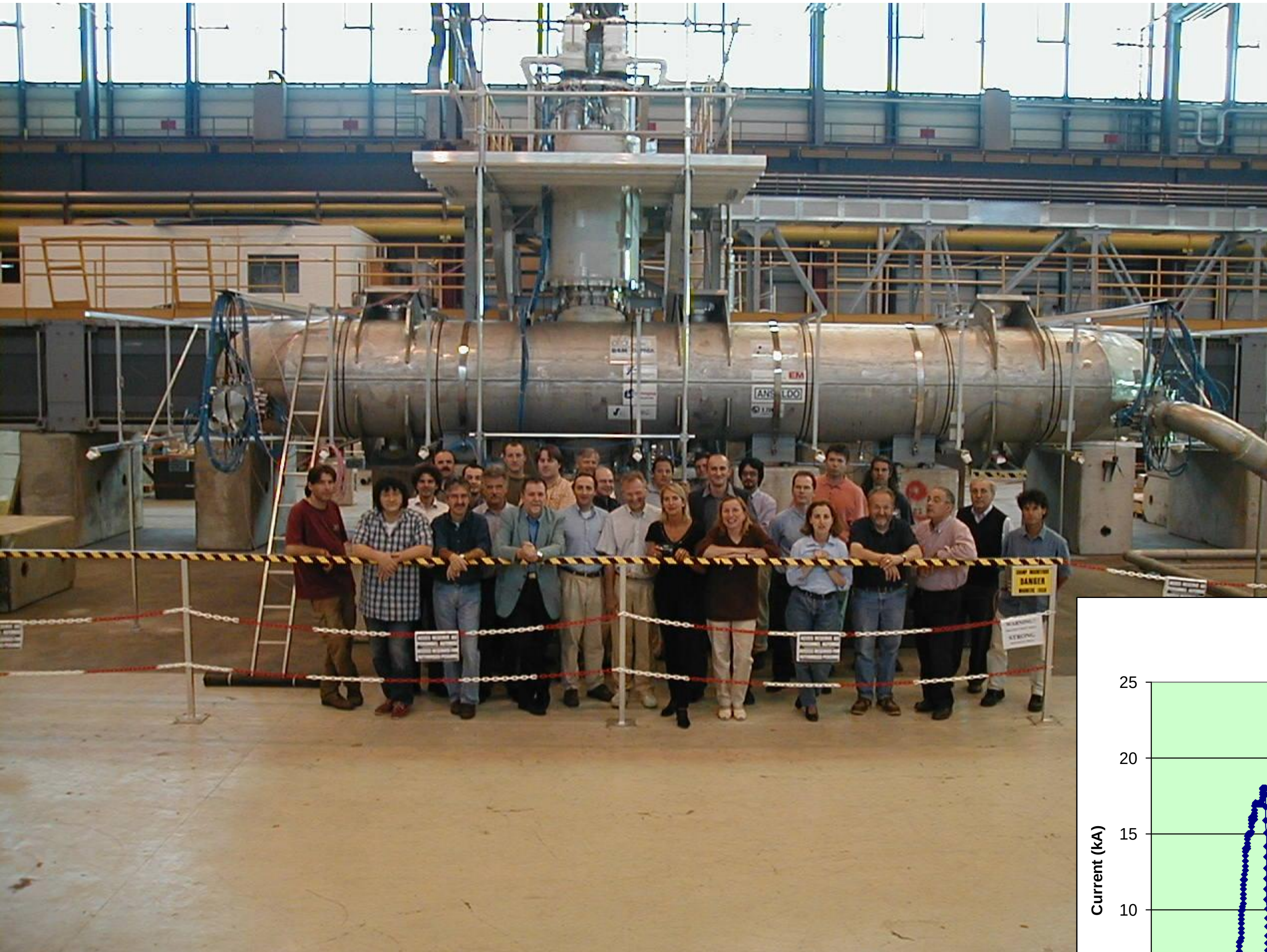
5.0 m axial length
10.7 m outer diameter
2x8 coils
2x0.25 GJ stored energy
2x160 tons cold mass
2x240 tons weight
4 T on superconductor
2x13 km Al/NbTi/Cu conductor
20.5 kA nominal current
4.7 K working point

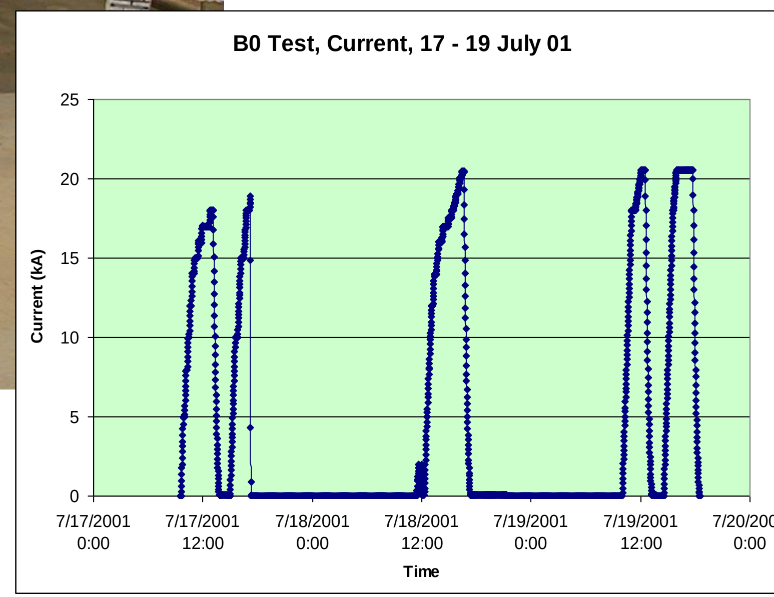
One of many ingredients to make the experiment affordable …



… initial ideas of a toroid with 12 coils were 'descoped' to a 8 coil design (which turned out to be an excellent choice also to have more 'air' in the air-core spectrometer)

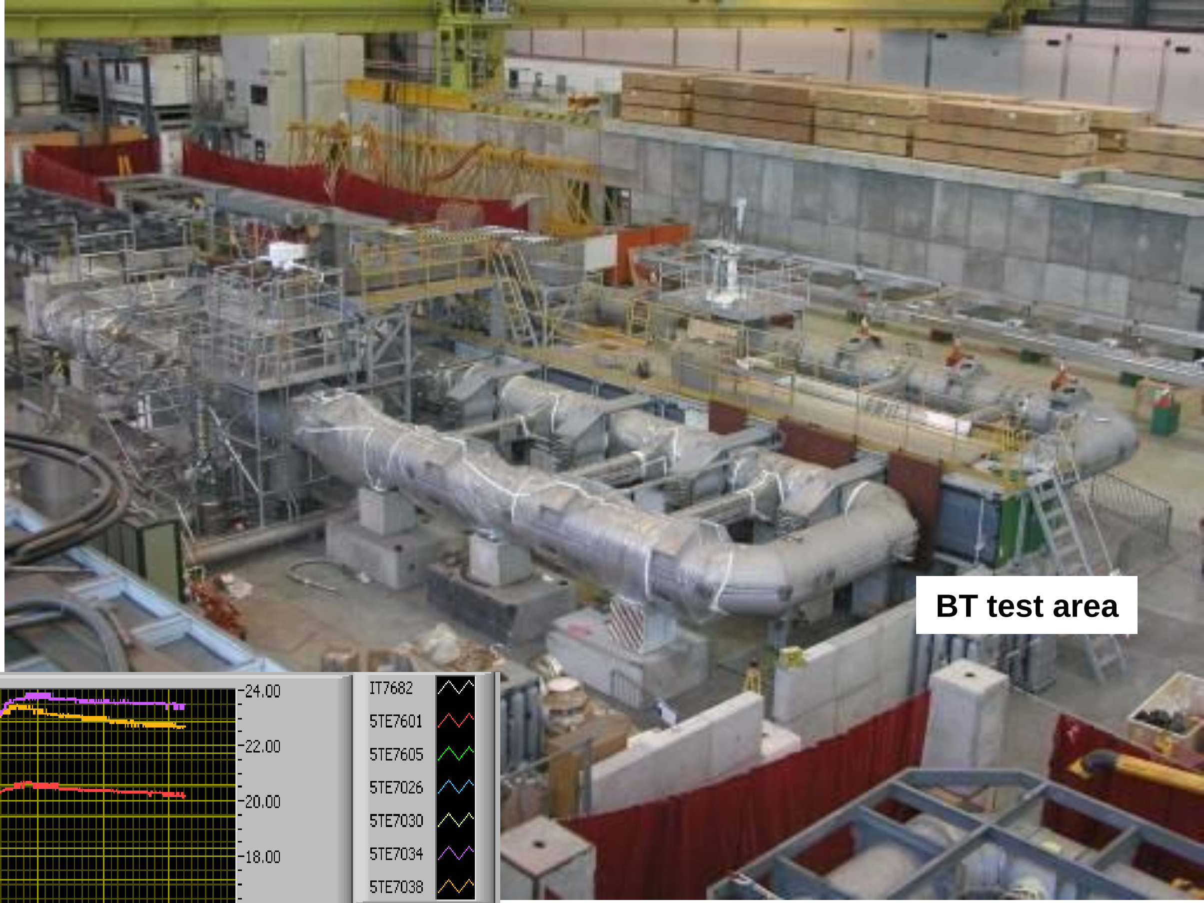
The B0 Model Coil Reaching Full Current of 20.5 kA in July 2001

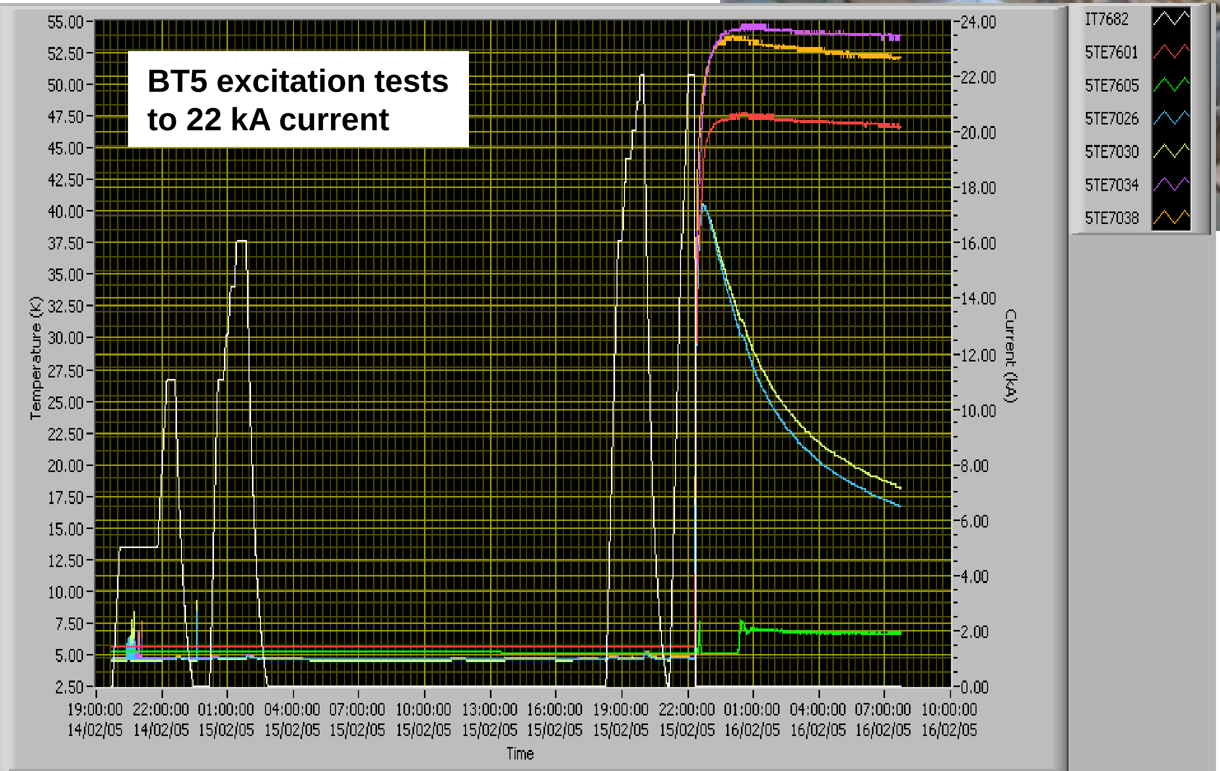




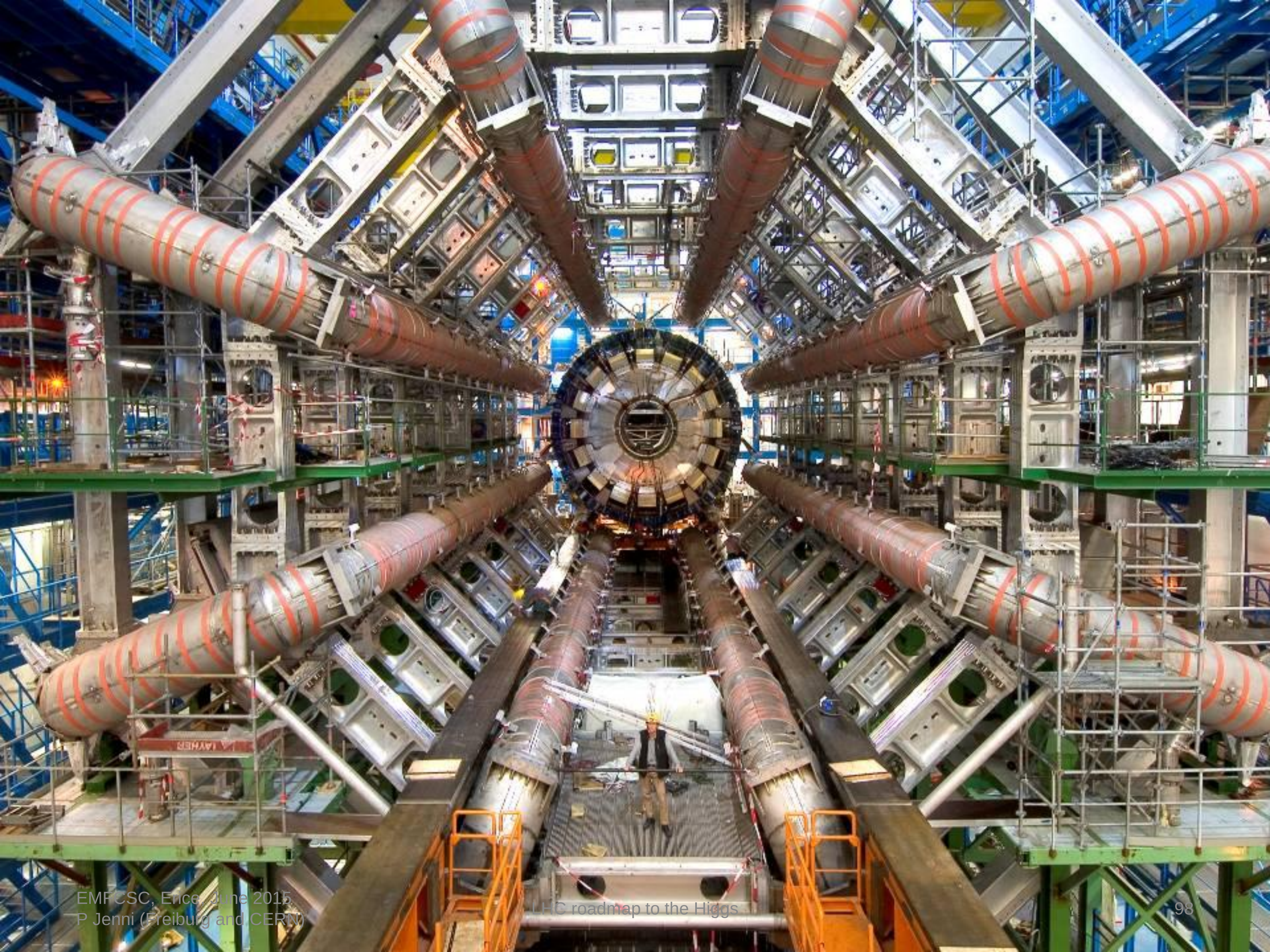
ATLAS Barrel Toroid construction

Series integration and tests of the 8 coils at the surface were finished in June 2005





First Barrel Toroid coil on its way to Point-1 (21-10-2004)

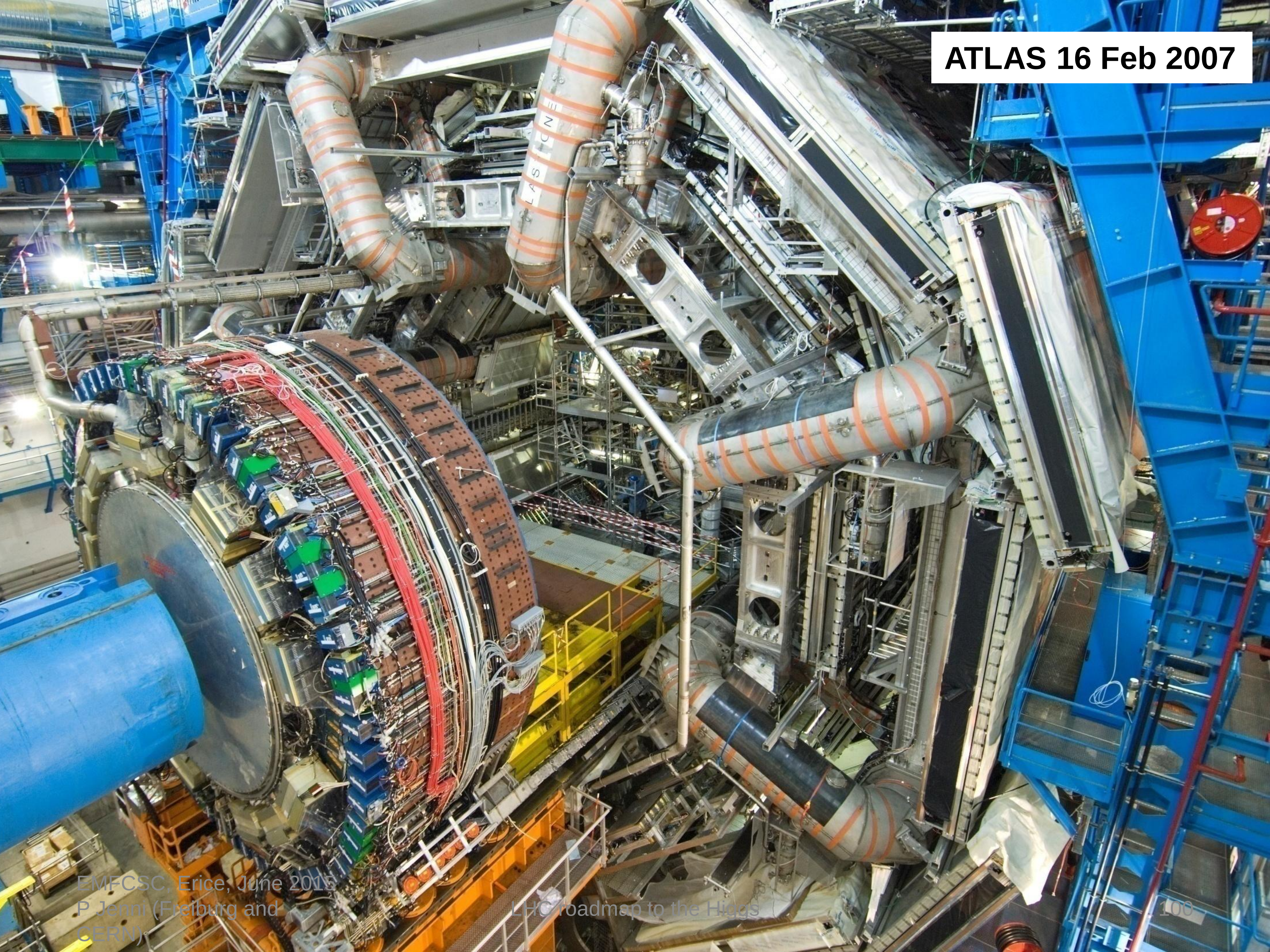


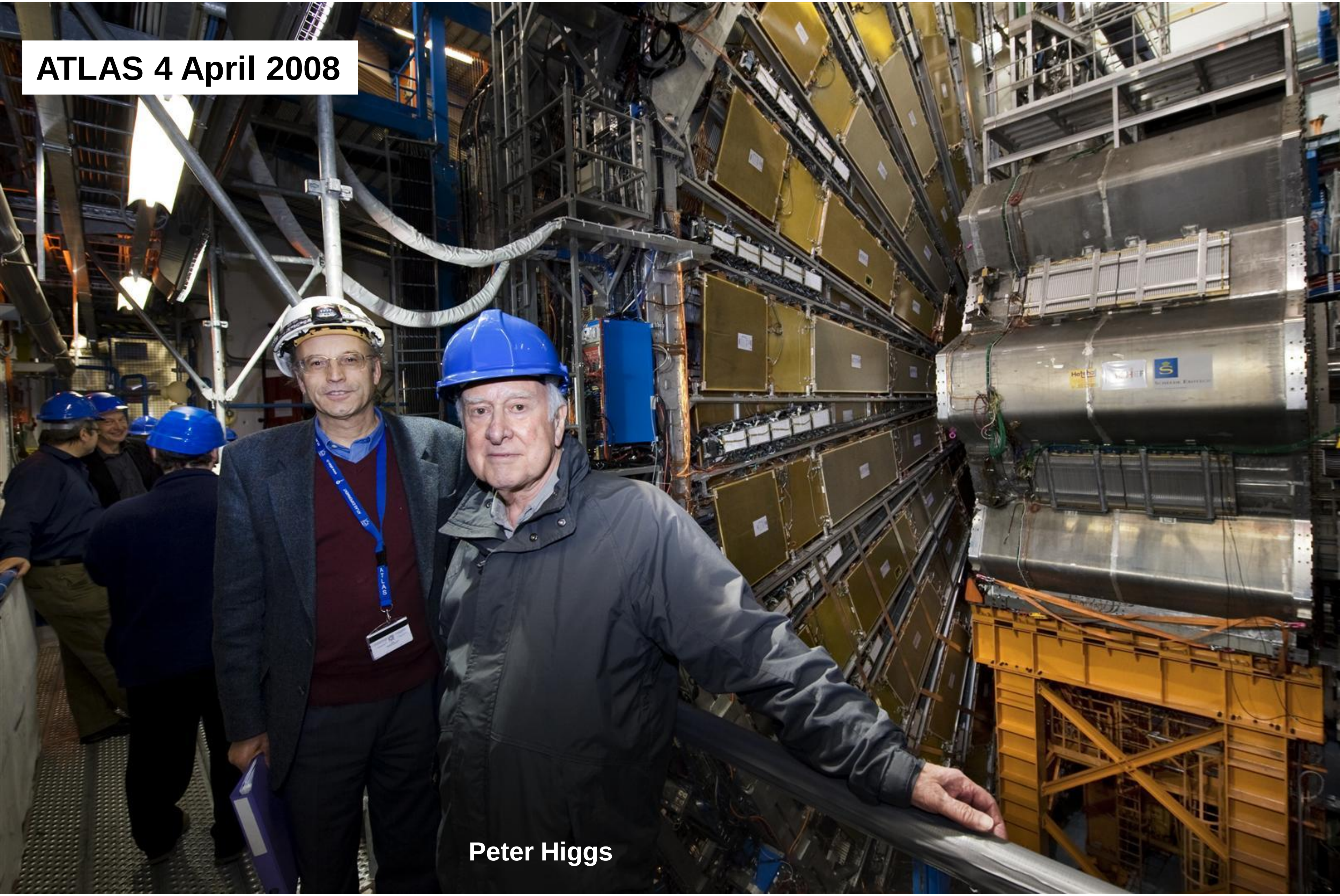
ATLAS End-cap Toroid installation, as an example

The transports and installations were major operations, involving also specialized firms

The ECTs are 250 tons, 15 m high, 5 m wide

ECT-A was lowered on 13th June 2007, and ECT-C on 12th July 2007


ATLAS 16 Feb 2007

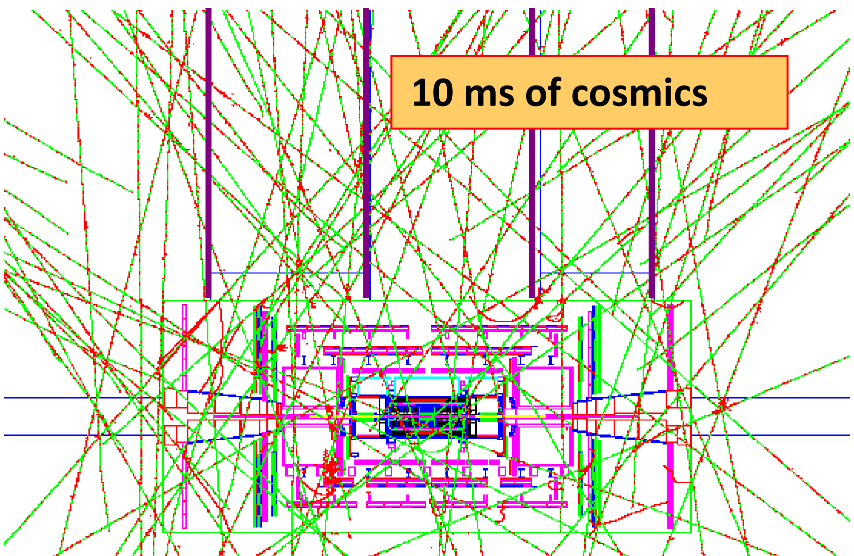

ATLAS 4 April 2008
Peter Higgs

A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008

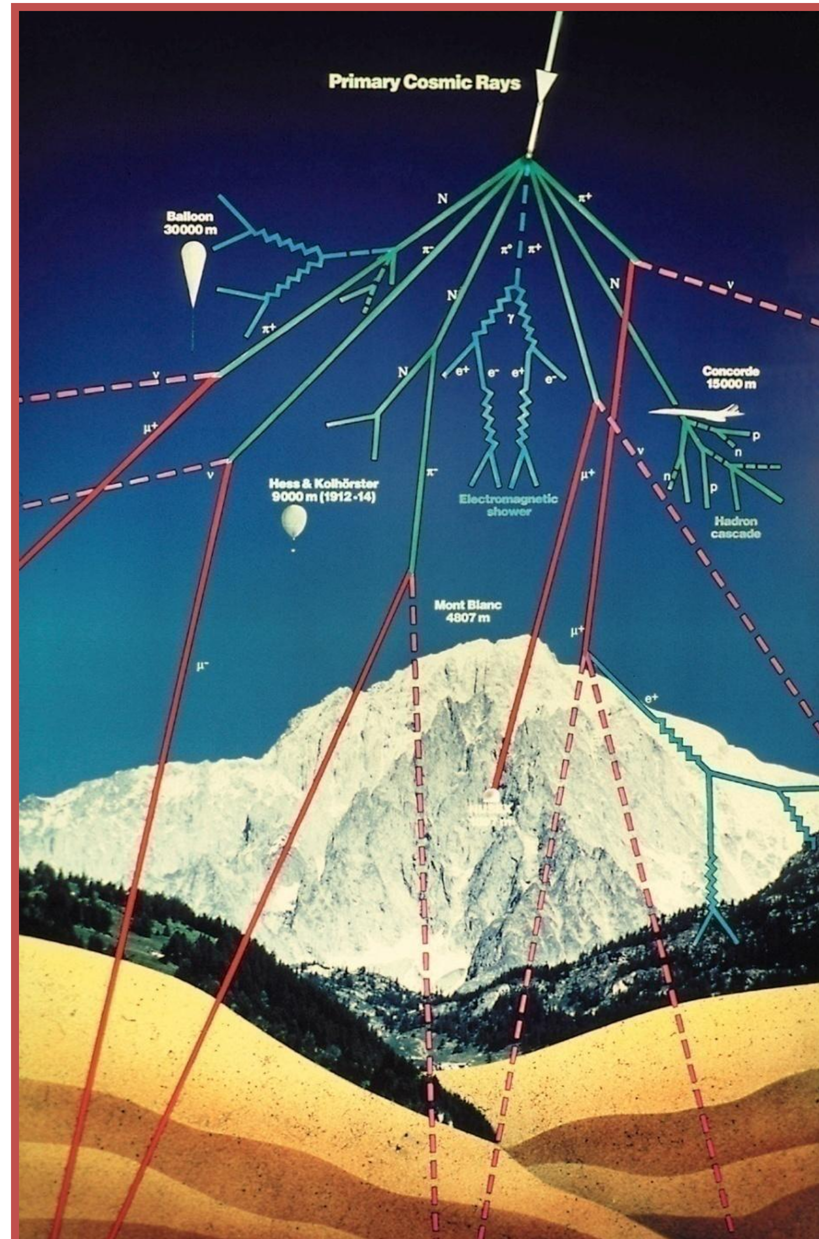
Commissioning with cosmics in the underground caverns
(the first real data in situ …)

Started when the first components were installed.
Very useful to:

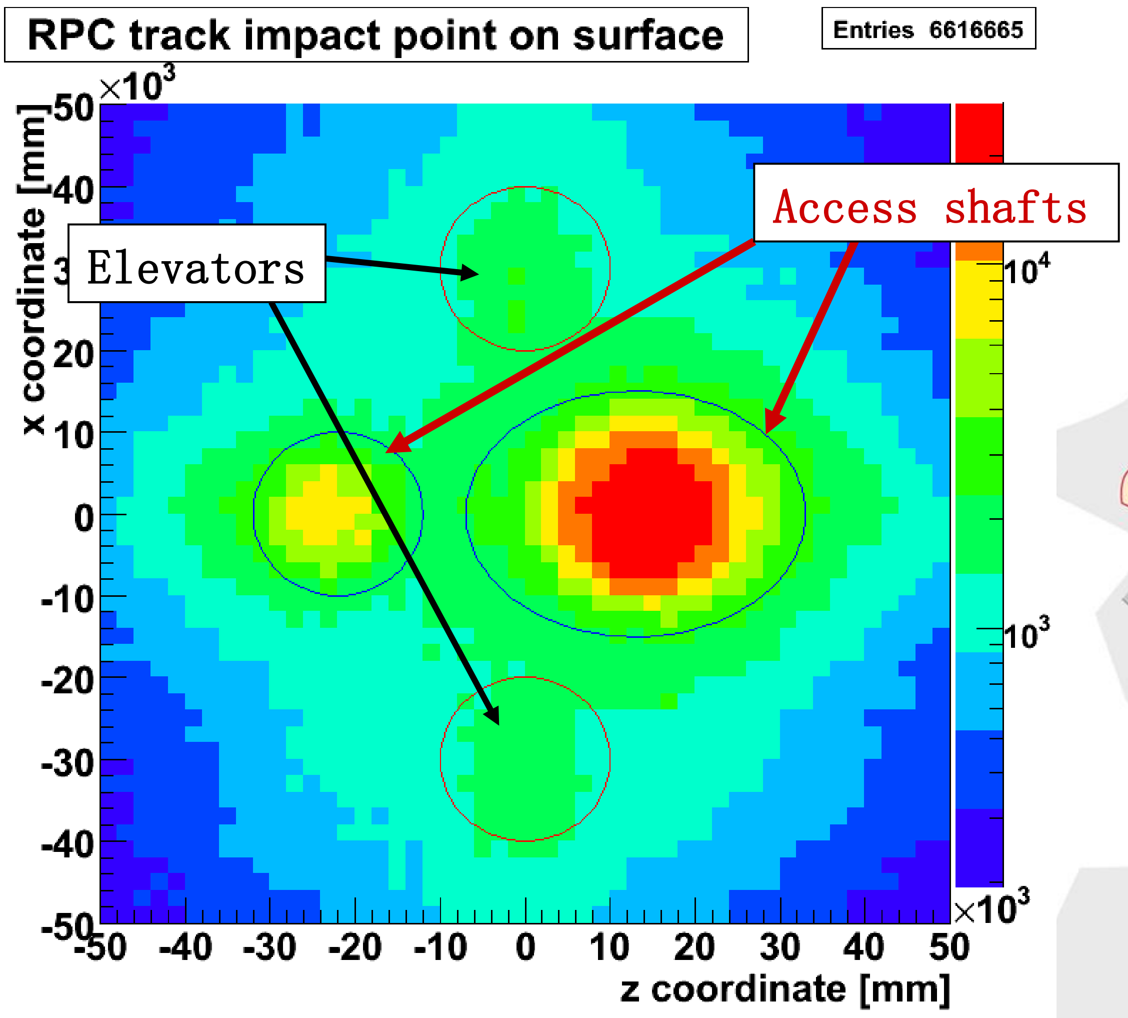
- **Run an increasingly more complete detector with final trigger, data acquisition and monitoring systems.** **Data analyzed with final software**
- **Shake-down and debug the experiment in its final position → fix problems**
- **Perform first calibration and alignment studies**
- **Gain global operation experience in situ before collisions start**

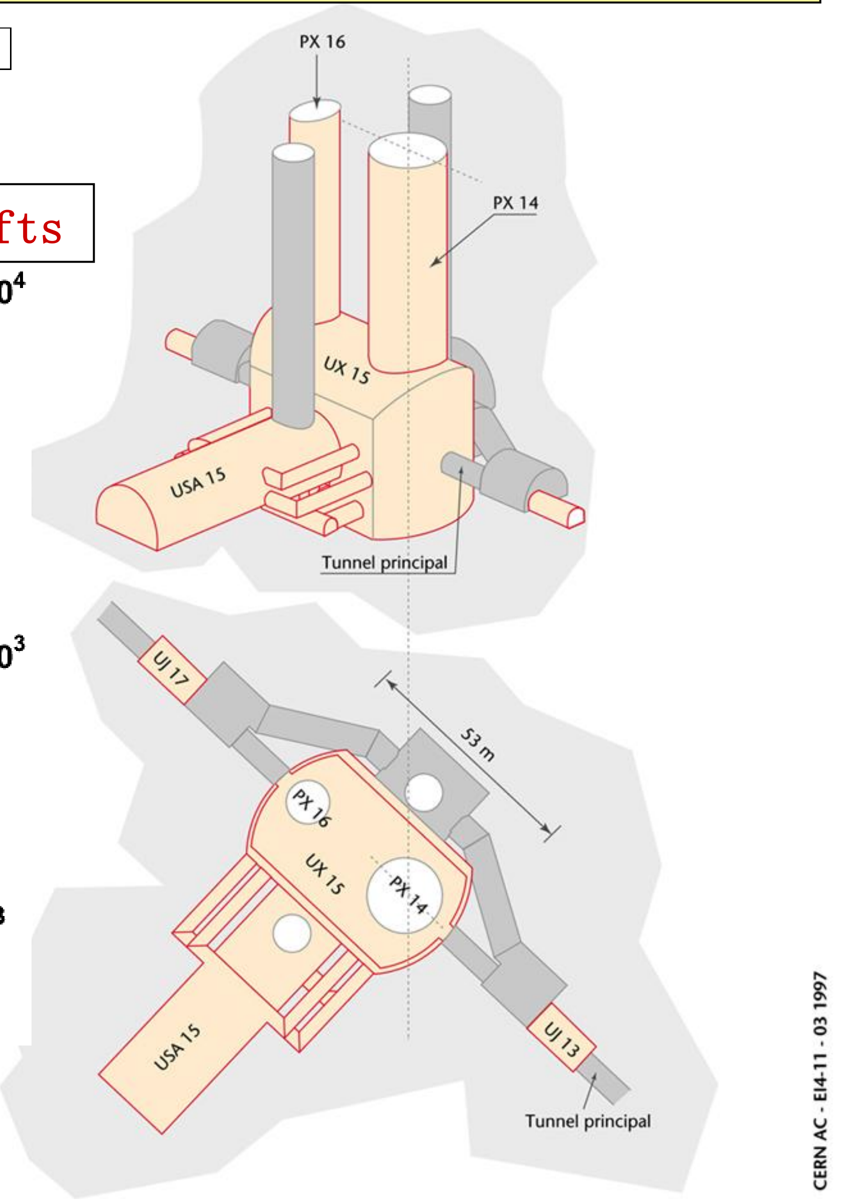


Rate of cosmics in ATLAS: 0.5-100 Hz
(depending on sub-detector size and location)

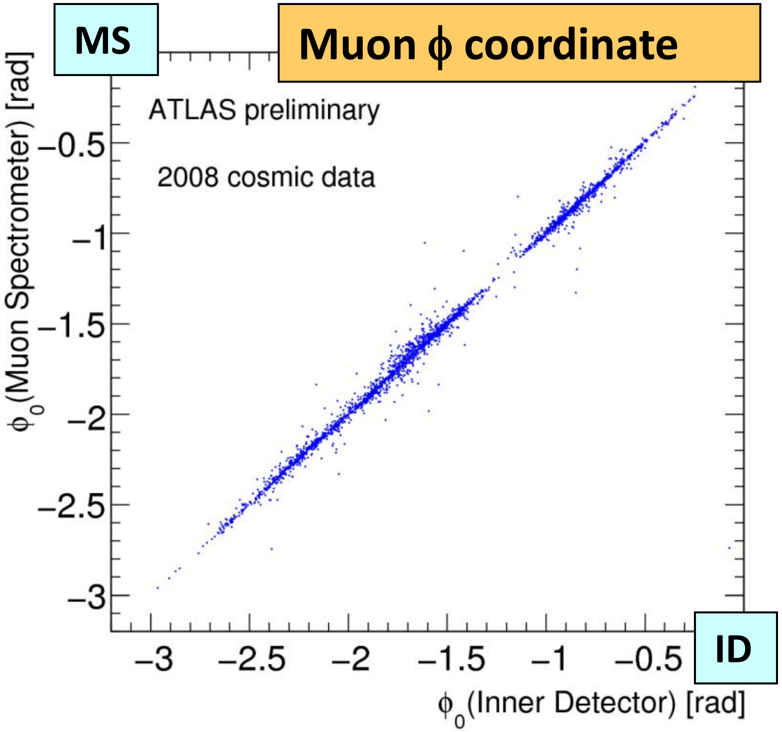


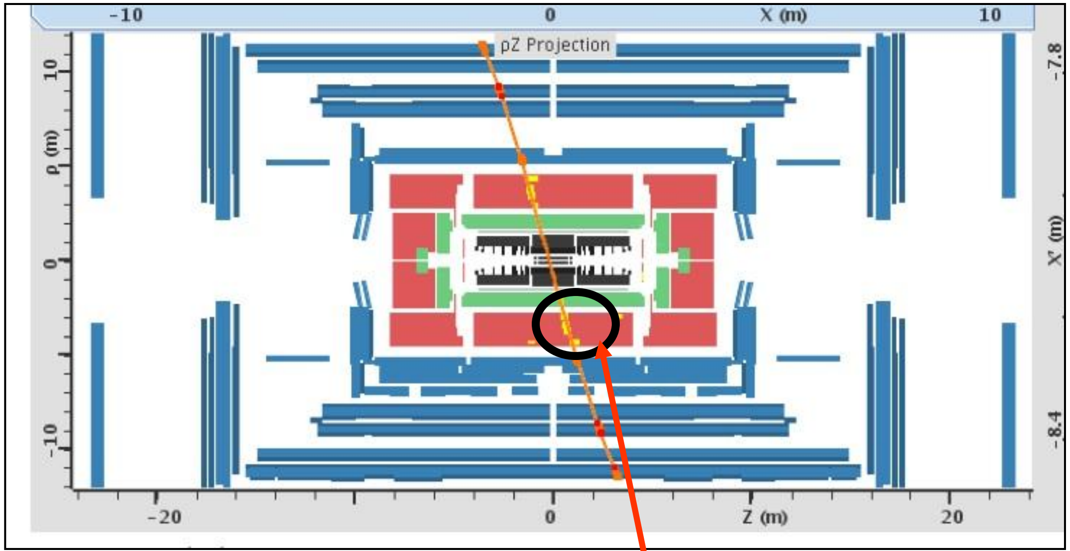
Extrapolation to the surface of cosmic muon tracks reconstructed by RPC trigger chambers



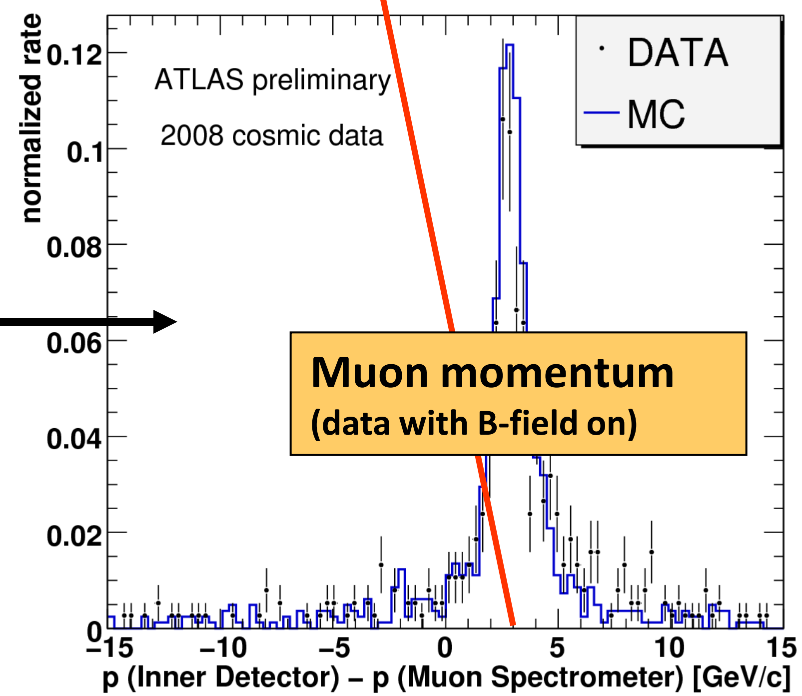


Correlation between measurements in the ATLAS Inner Detector and the Muon Spectrometer





Difference between the muon momentum measured in the ID and in the MS for tracks in the bottom part of the detector (~ 3 GeV energy loss in the calorimeter)



Expected energy loss by dE/dx in the ATLAS calorimeter

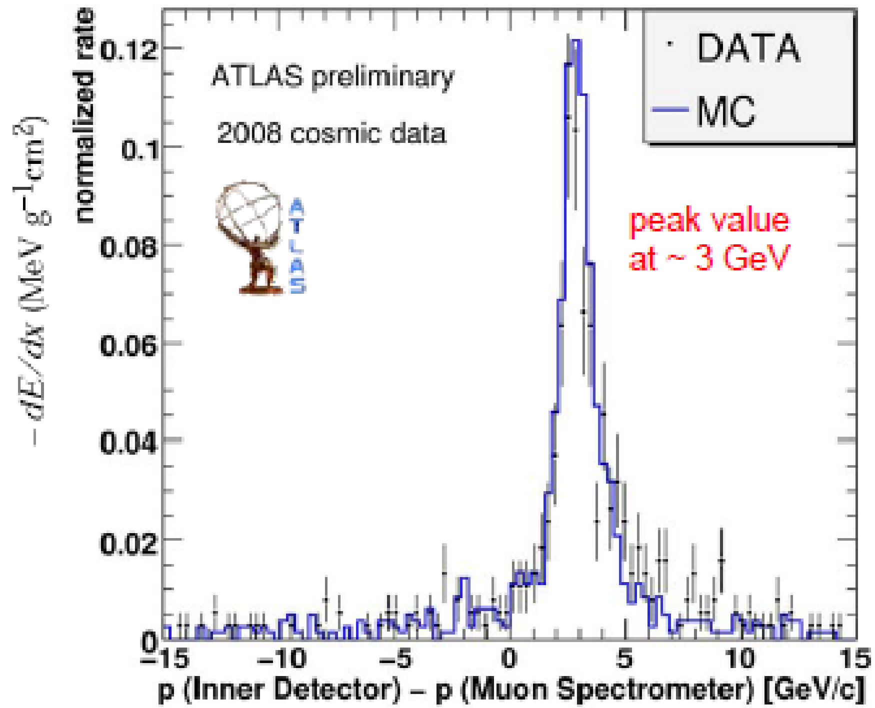
Back-on-the-envelope:

HAD cal: $200\text{cm}\cdot\left(0.4\cdot\left.\frac{dE}{dx}\right|_{Fe}\cdot 11.8\frac{g}{cm^3}+0.6\left.\frac{dE}{dx}\right|_{C}\cdot 2\frac{g}{cm^3}\right)=2.1\text{ GeV}$

EM cal: $100\text{cm}\cdot\left(0.4\cdot\left.\frac{dE}{dx}\right|_{Pb}\cdot 16.9\frac{g}{cm^3}\right)=1.0\text{ GeV}$

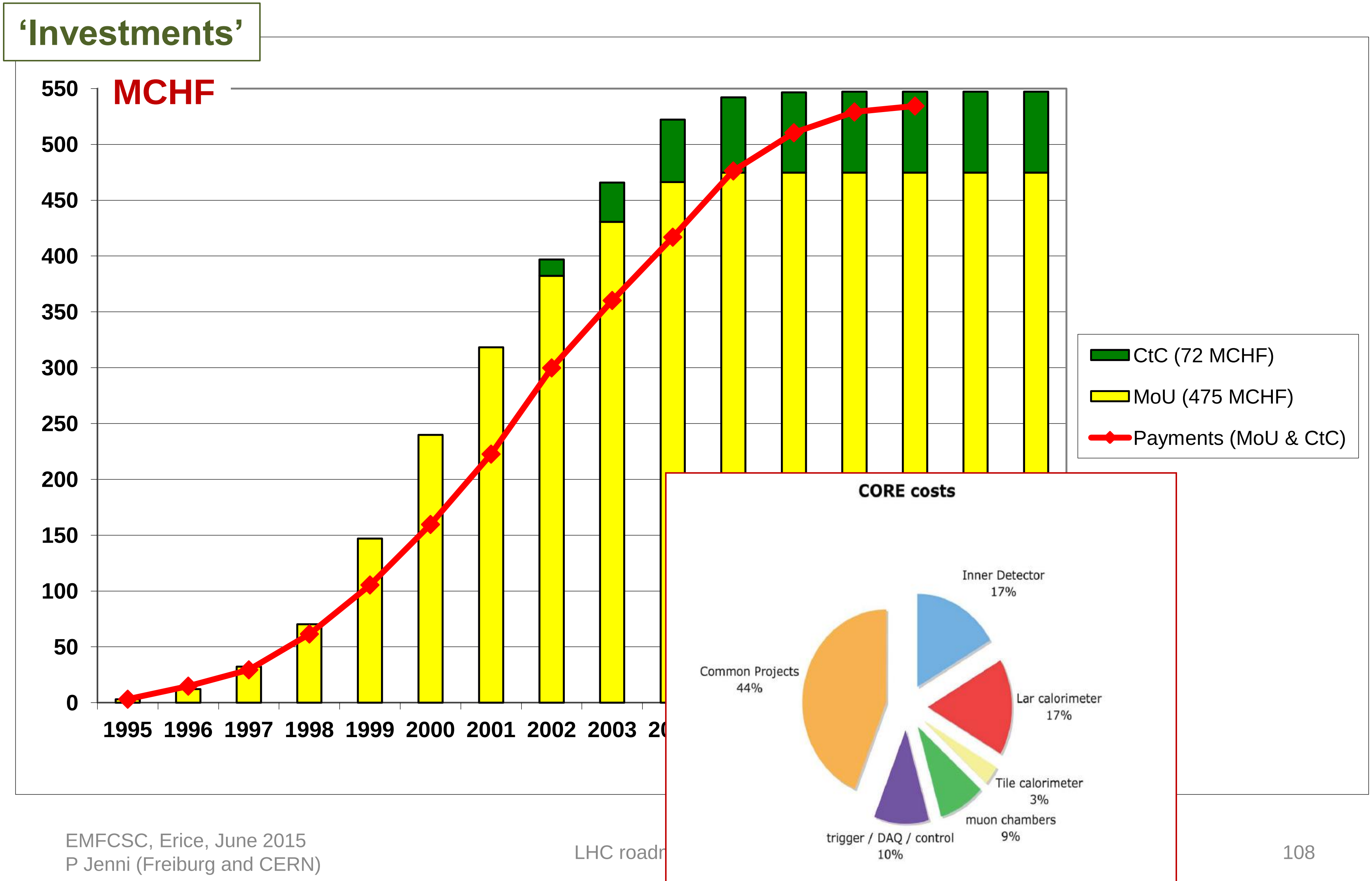
Solenoid: $5\text{cm}\cdot\left(\left.\frac{dE}{dx}\right|_{Cu}\cdot 8.9\frac{g}{cm^3}\right)=0.1\text{ GeV}$

~ 3.2 GeV muon energy loss



Since 1995 we had the Resources Review Board meetings twice a year (here all financial matters are agreed with the Funding Agency delegates, and the execution of the formal Memoranda of Understanding are monitored)

Overview of the integrated financial evolution of the 'CORE' costs of ATLAS (Construction MoU deliverables and Common Fund, Cost-to-Completion, in MCHF)



Strategy toward physics

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✔

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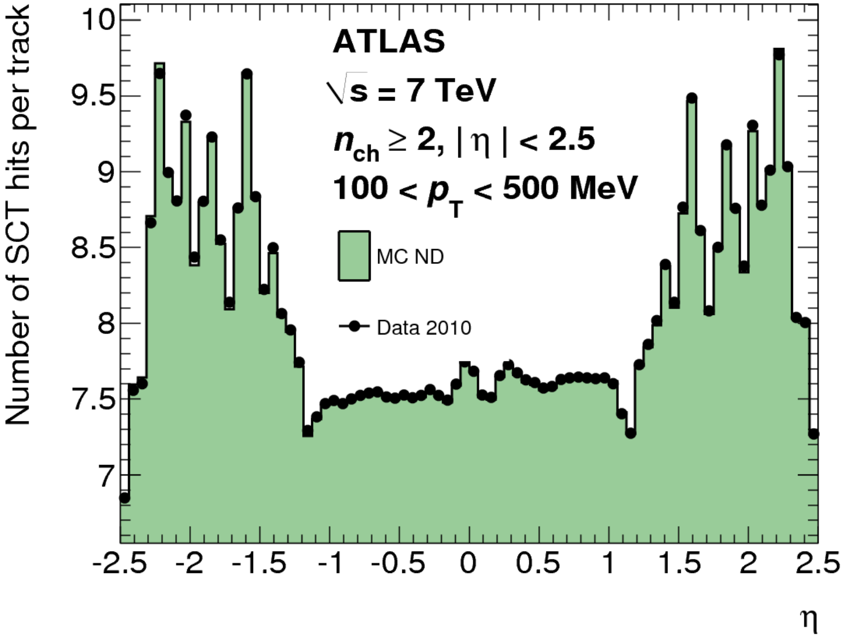
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

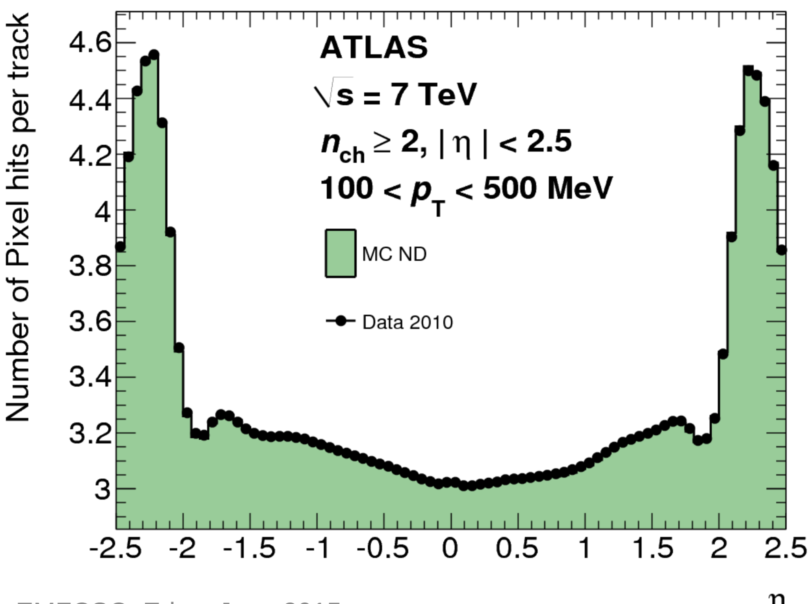
Prepare the road to discoveries …

Examples of detector commissioning with collision events

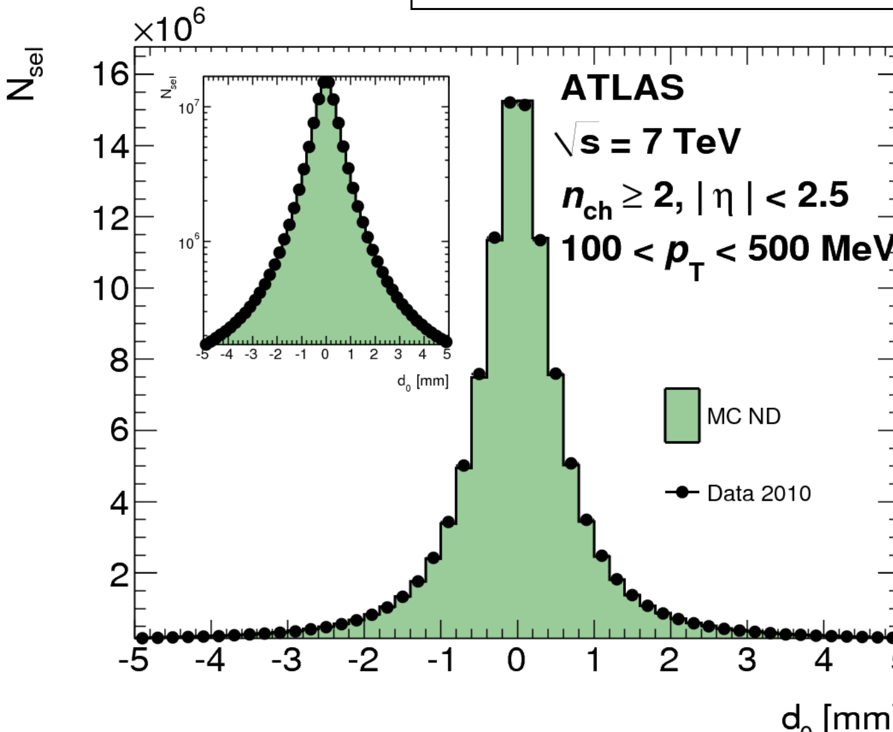
The tracking detector simulations are in a mature state, charged track measurements are well understood

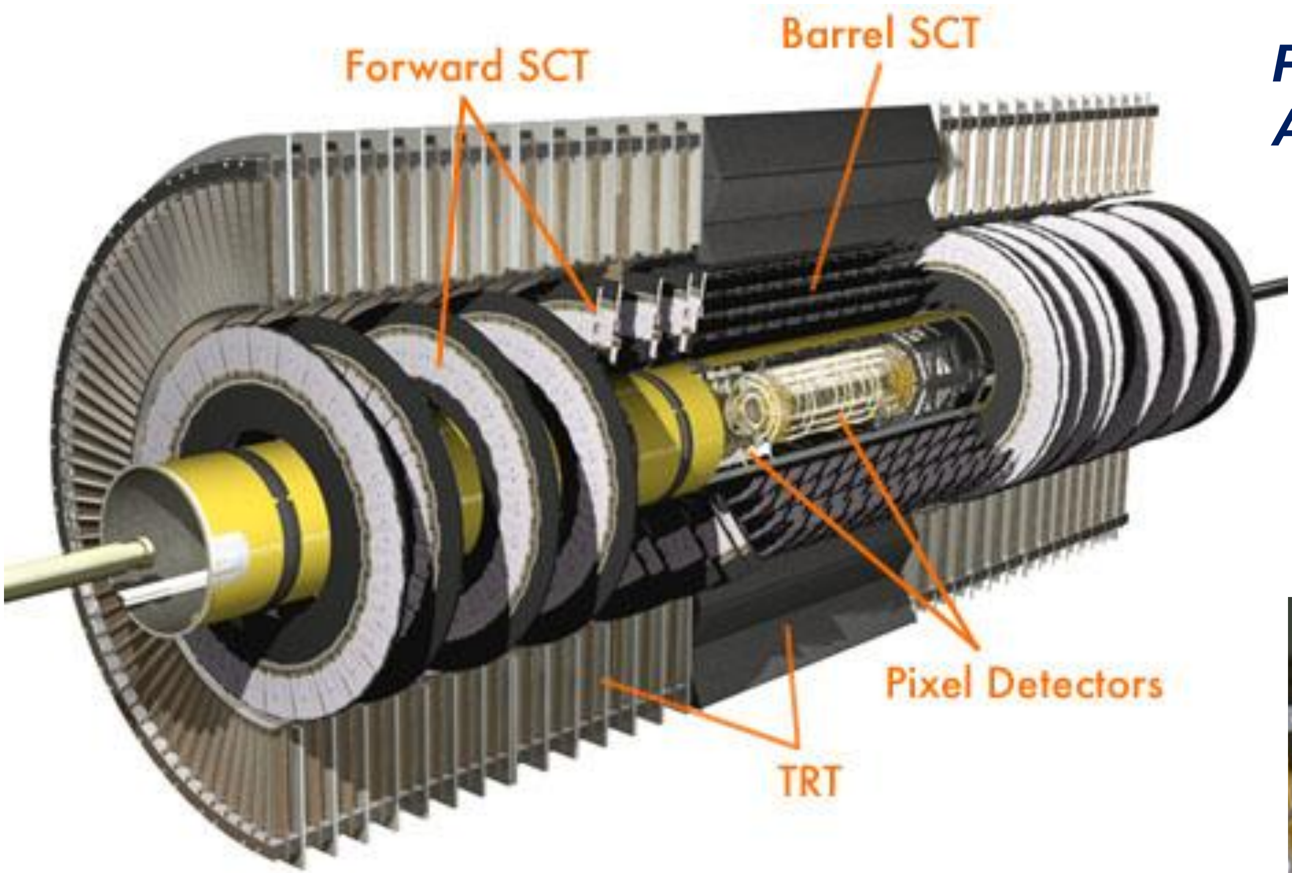
Example shows the ATLAS description of minimum bias tracks (silicon and pixel hits, transverse impact parameter)





New J. Phys. 13 (2010) 053033

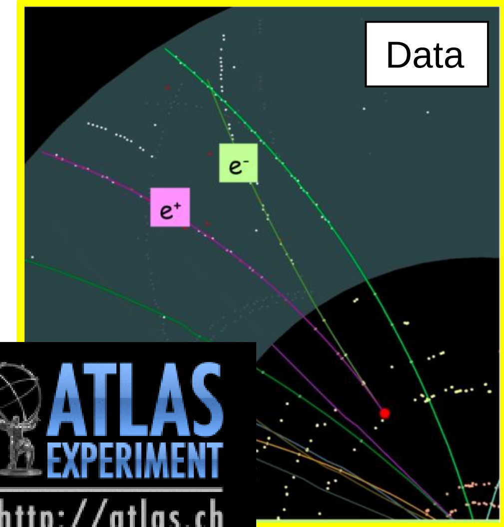




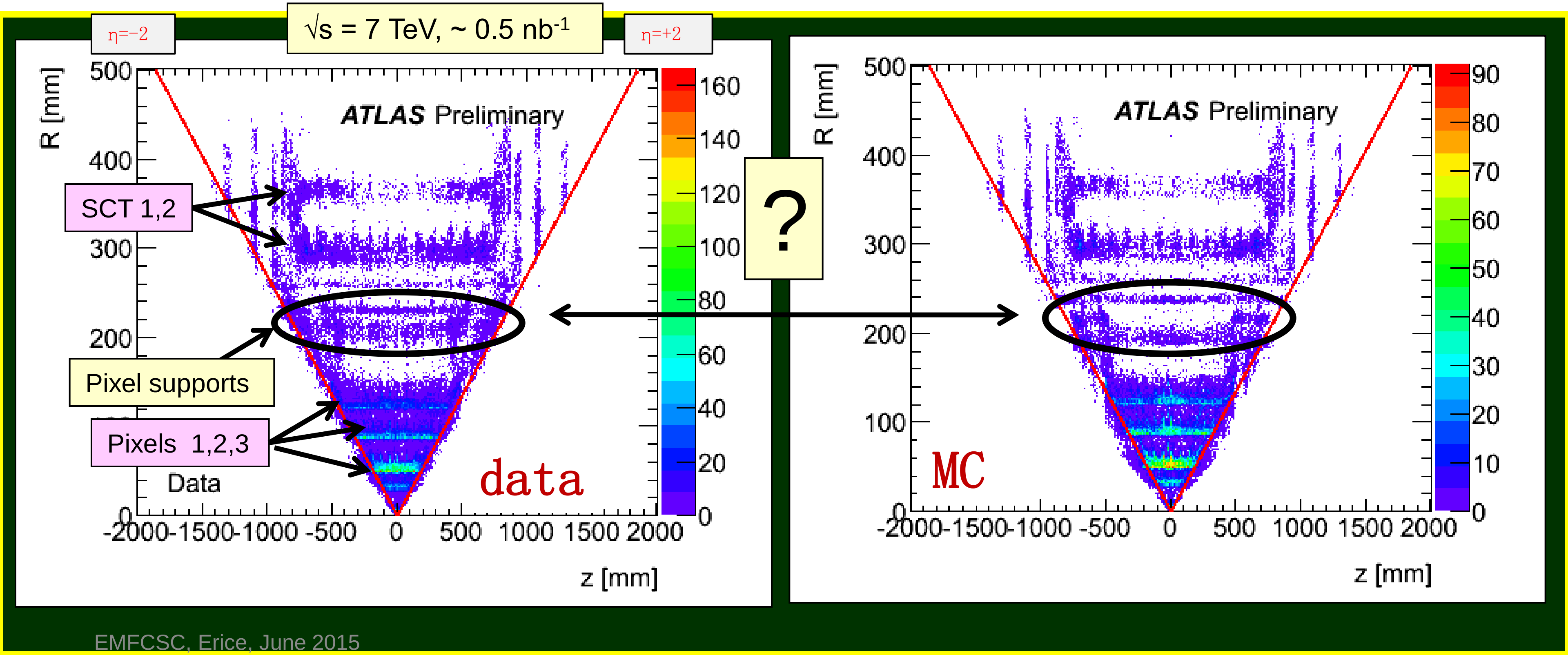
Reminder of the ATLAS Inner Detector

Mapping the Inner Detector material with $\gamma \rightarrow e^+e^-$ conversions

… and using data to find geometry imperfections in the simulation



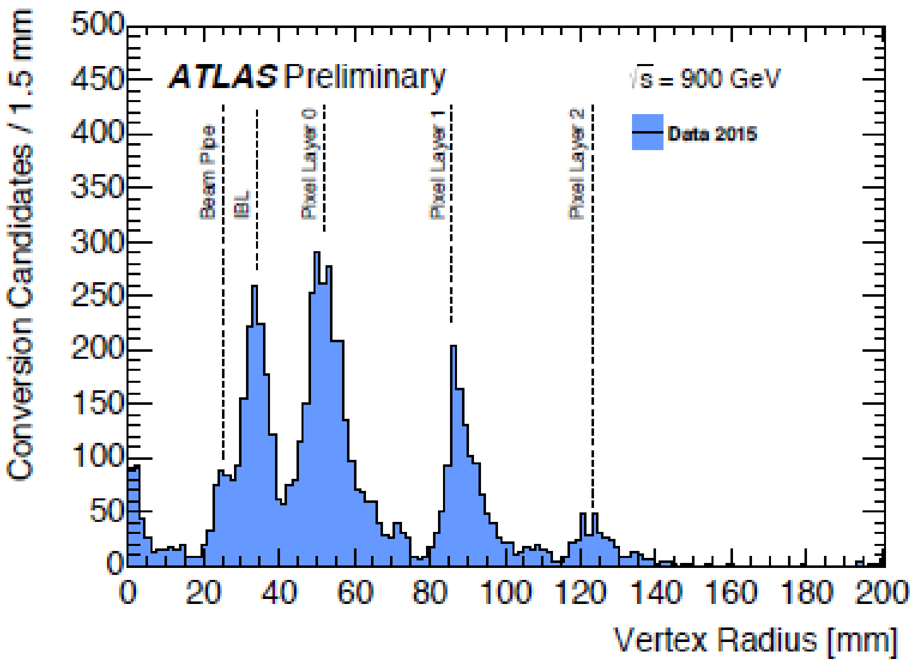
Reconstructed $\gamma \rightarrow e^+e^-$ conversion points in the Rz plane in minimum bias events



A very recent example from this year's start-up with a newly installed 4th Pixel layer in ATLAS (called 'IBL', standing for insertable B-layer')

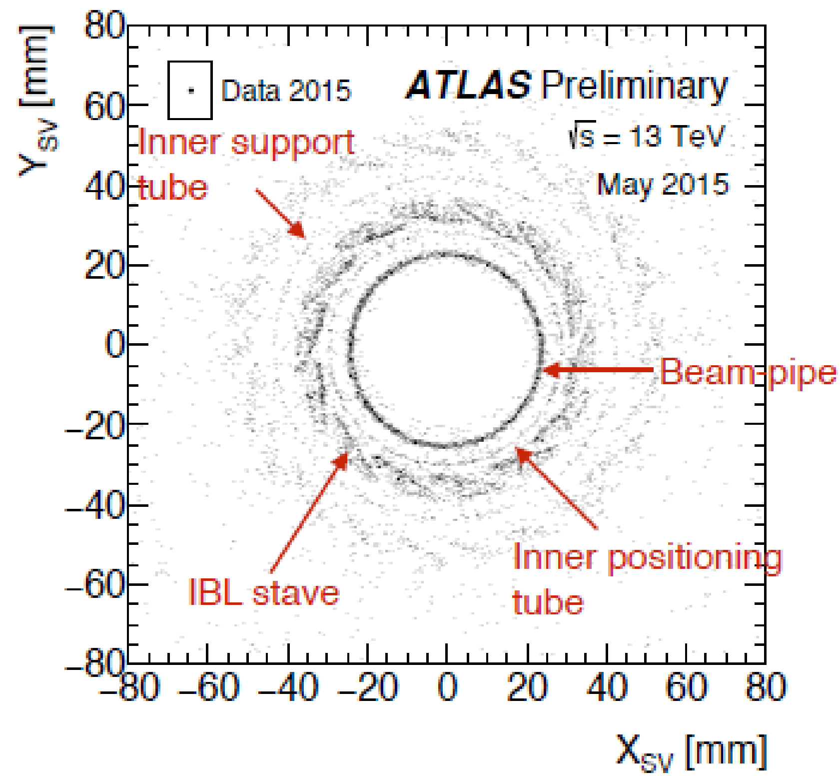
Conversions

Radial vertex position for photon conversion candidates.

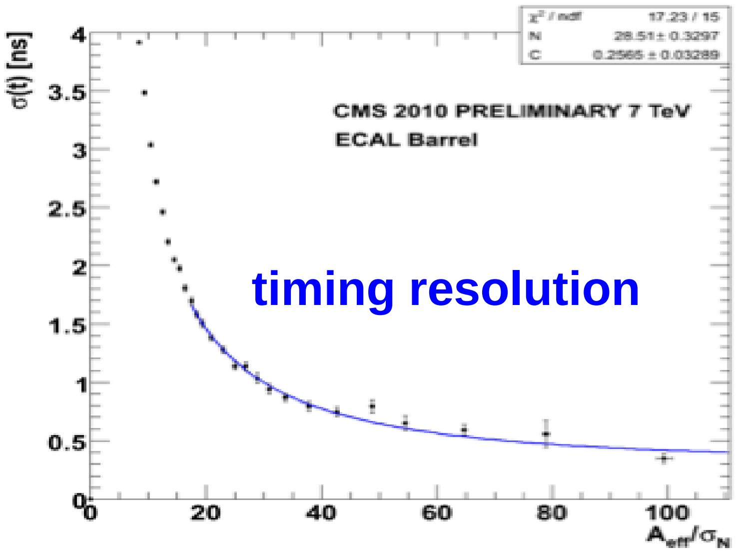


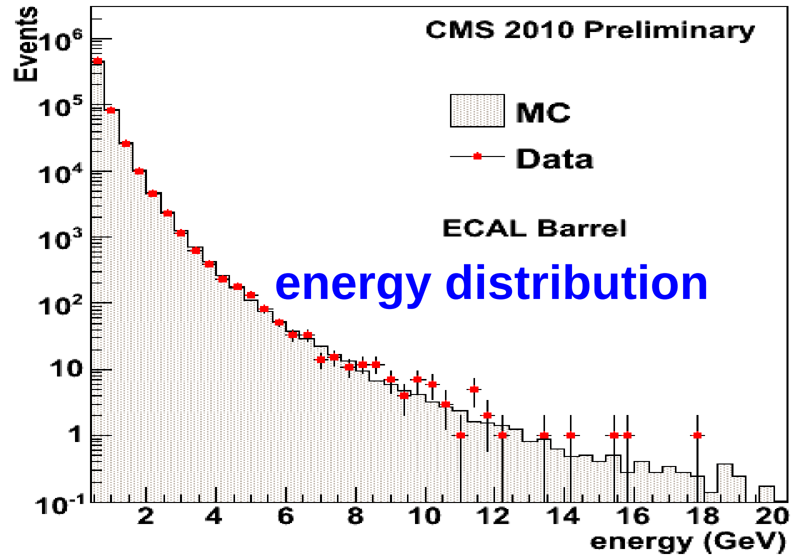
Hadronic interactions ("radiography")

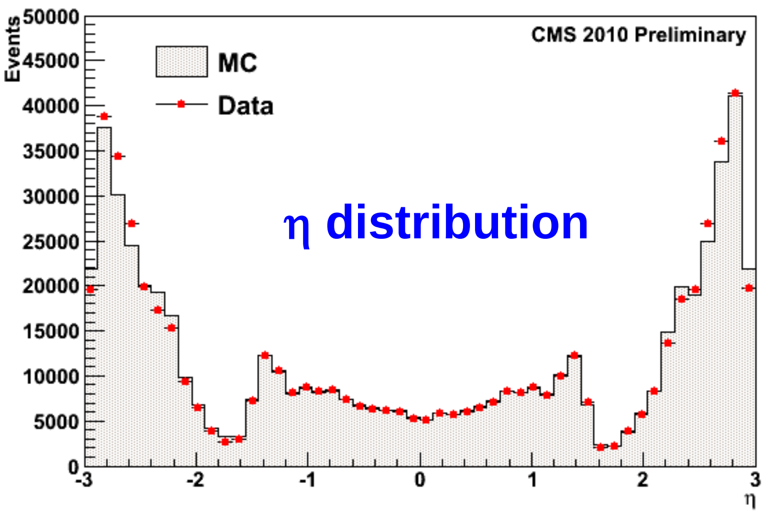
Vertex position for had. int. candidates in xy-plane, reconstructed from multiple tracks.

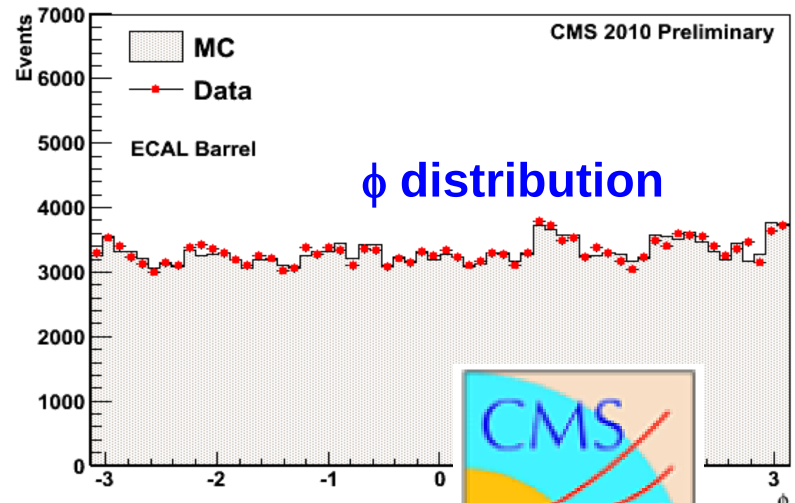


ECAL clusters (electrons and photons)



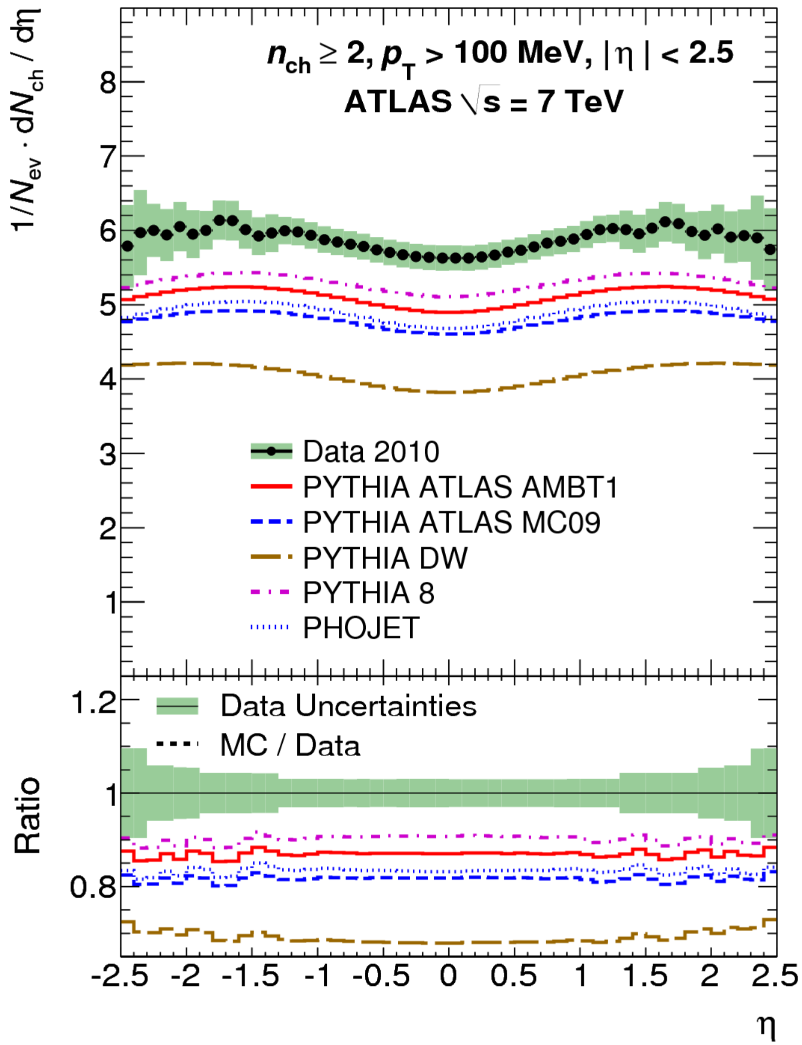


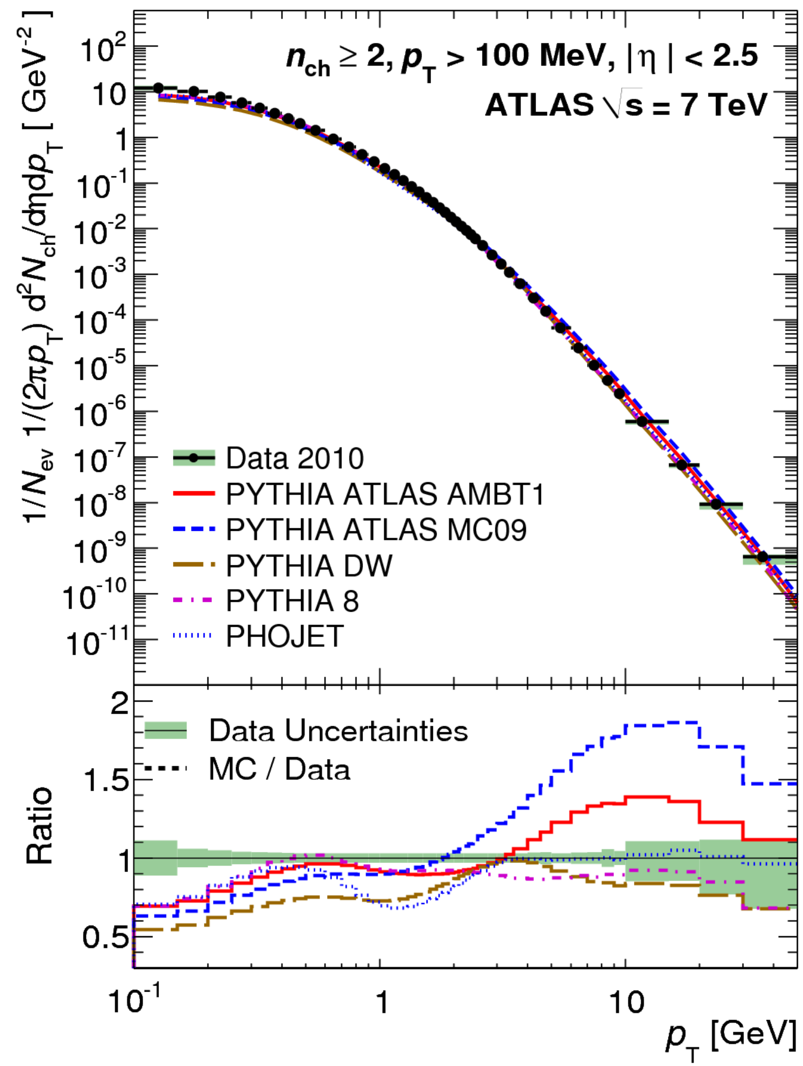




Charged-particle multiplicities as a function of pseudorapidity η and transverse momentum p_T for minimum bias events selected as specified, and compared to various Monte Carlo models

New J. Phys. 13 (2010) 053033

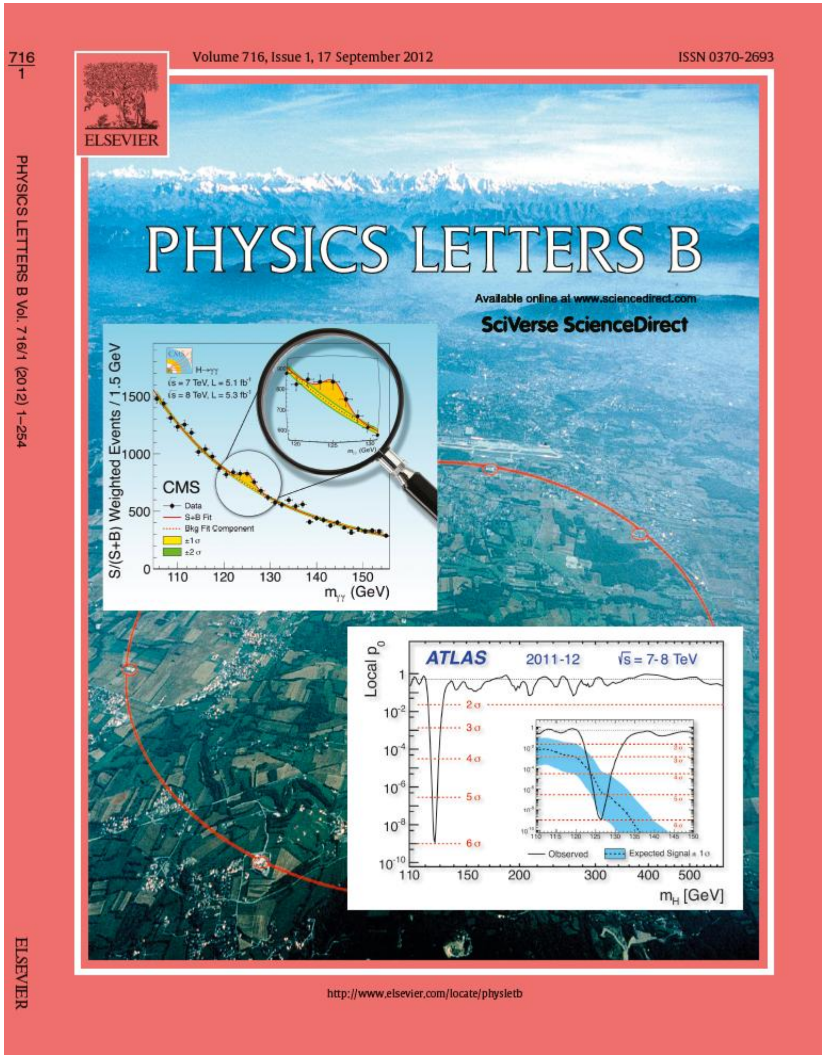




LHC Physics Highlights

ATLAS and CMS have already published together more than 800 papers in scientific journals (and many more as public conference notes…)

The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 400 journal publications together



Note that all public results are available from the experiments Web pages, and from the CERN Document Server
http://cdsweb.cern.ch/collection/LHC%20Experiments?ln=en

and on the public physics web sites of the Collaborations

Physics Highlights:

General event properties

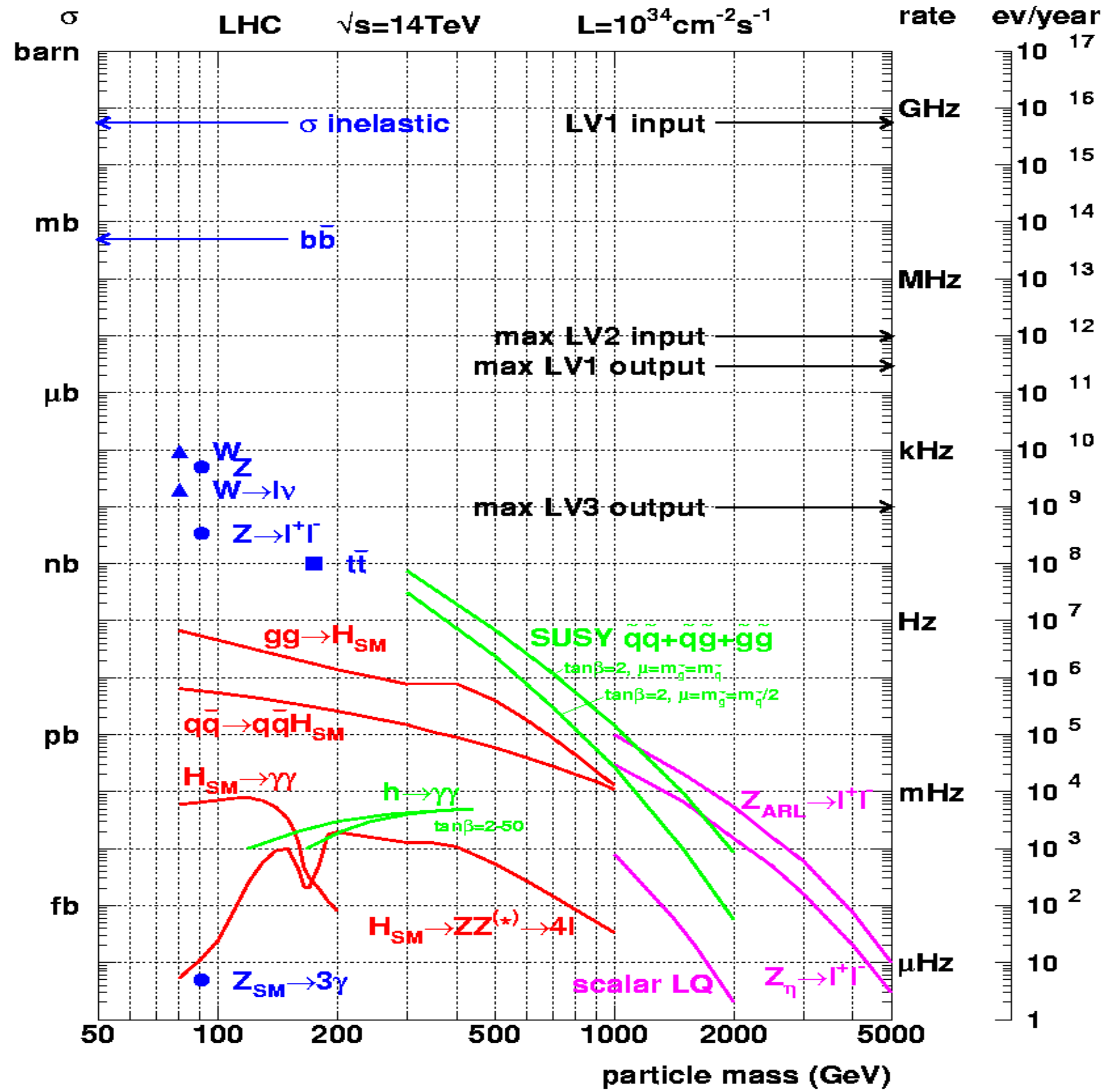
Heavy flavour physics

Standard Model physics including QCD jets

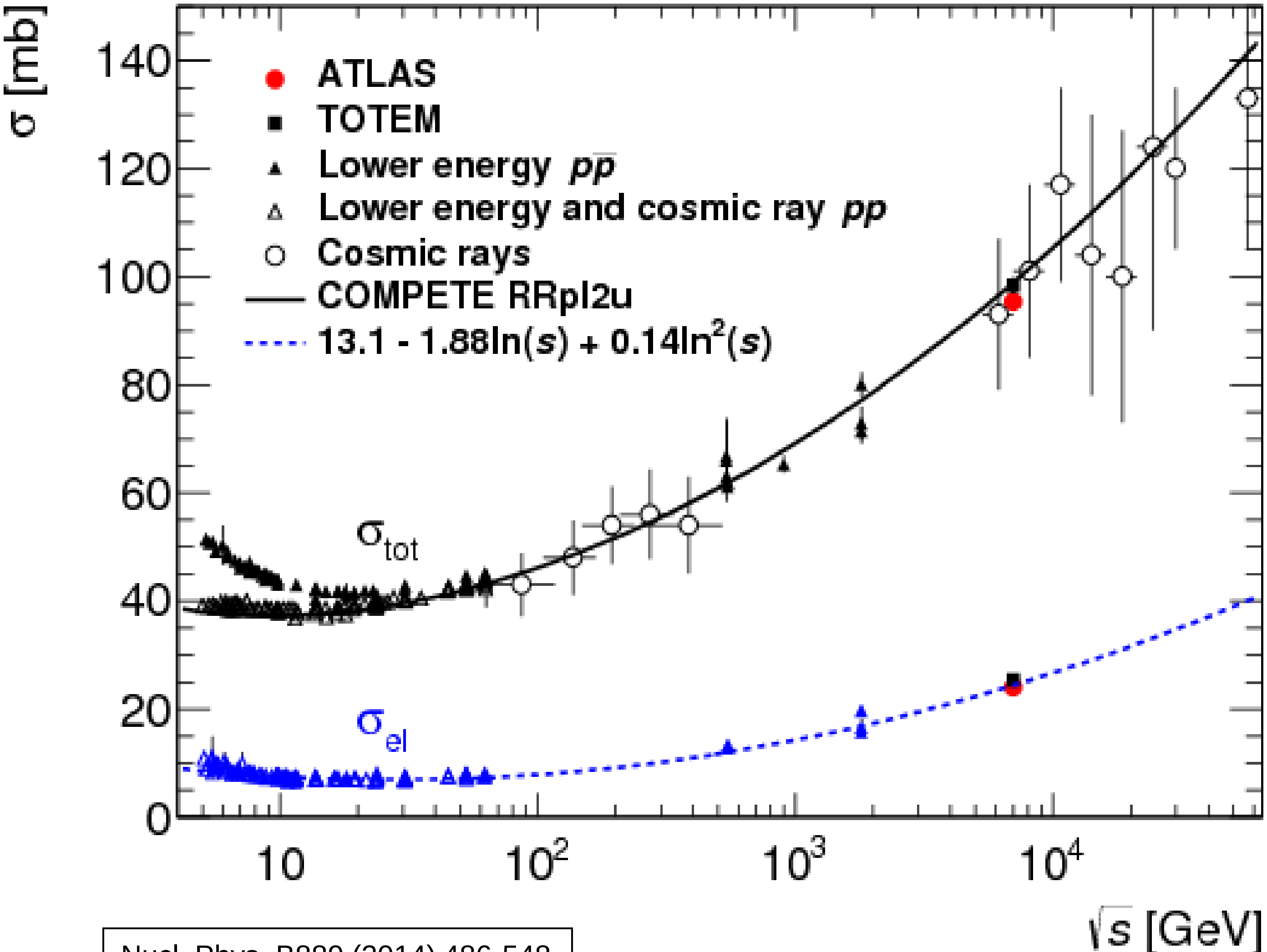
Higgs searches

Searches for SUSY

Searches for 'exotic' new physics

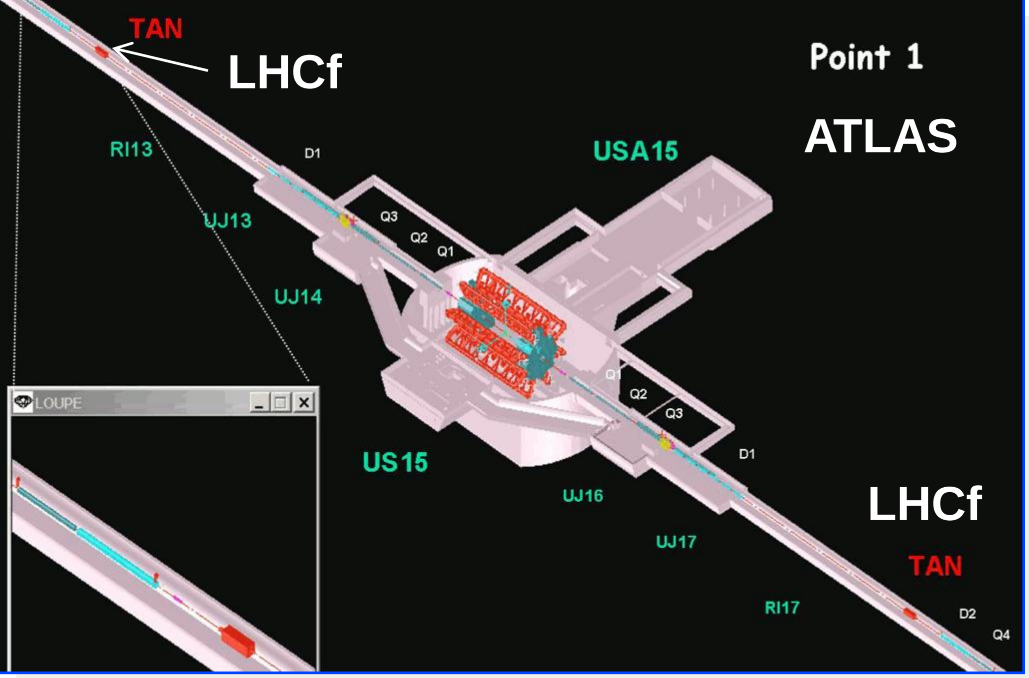


Very basic measurement: the total cross-section
('measure of the total interaction probability when two protons hit each other')

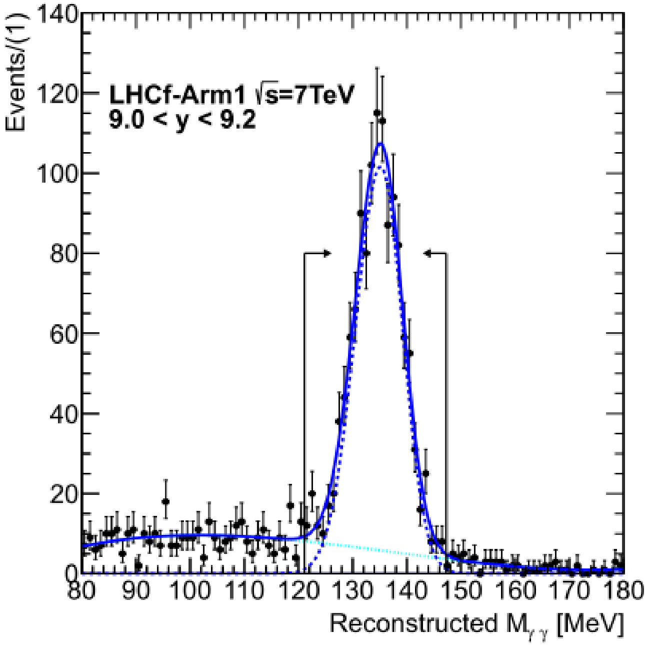


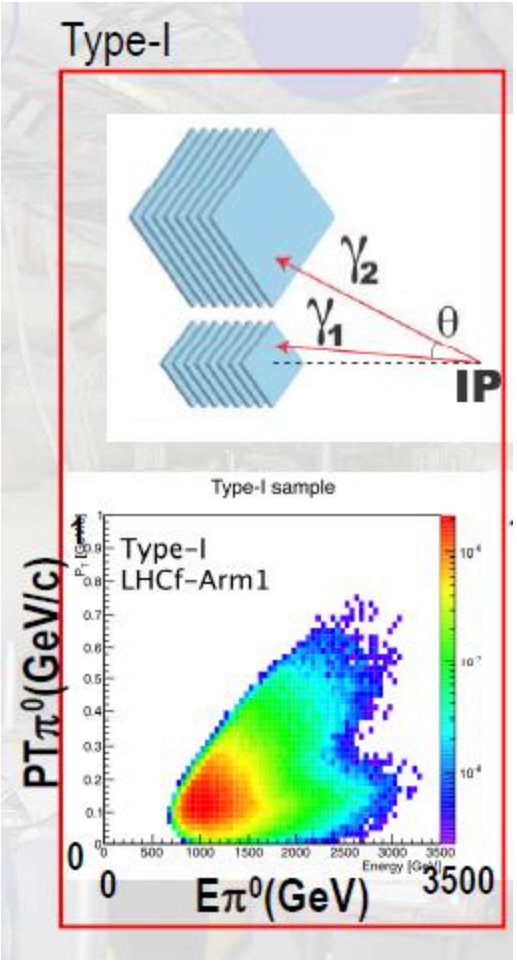
Nucl. Phys. B889 (2014) 486-548

But remember, only once in about 10^{13} of the collisions a detectable Higgs is produced



LHCf 7 TeV π^0 signal



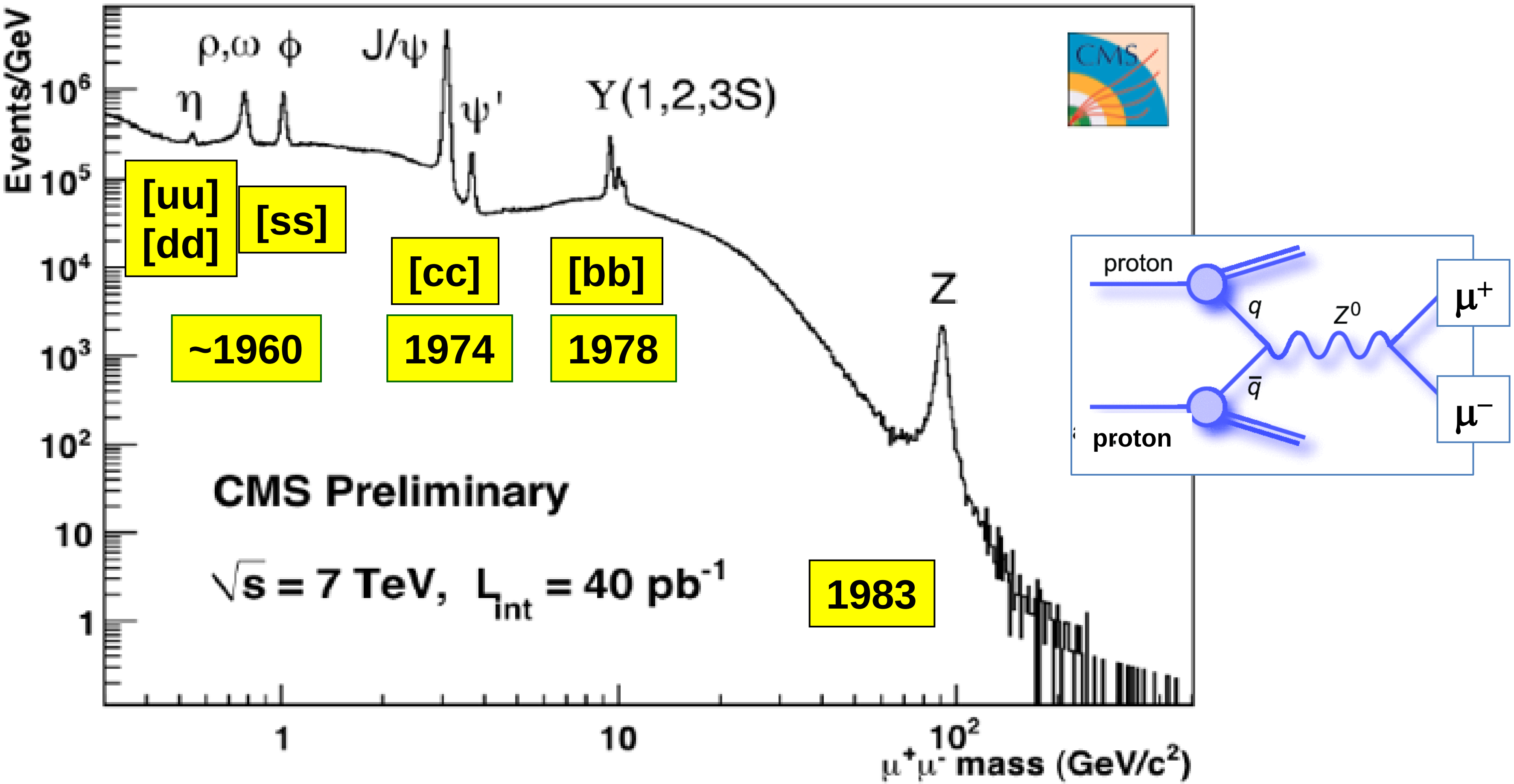


Feedback to modeling of Ultra High Energy Cosmic Rays (UHERCs)

Presented at HCP2012

2010

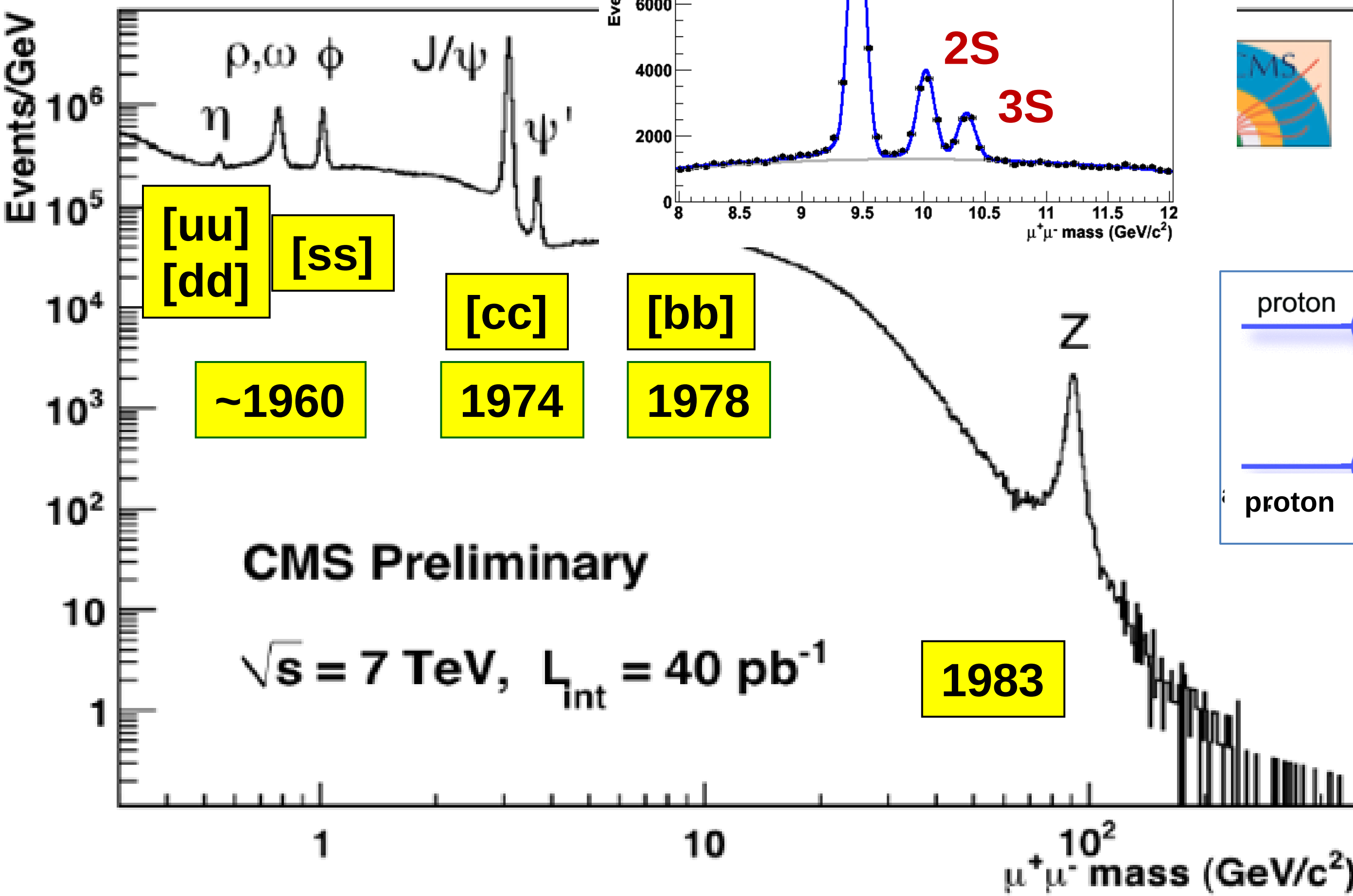
Data corresponding to ~40 pb^{-1} collected
→ re-discovery of the Standard Model

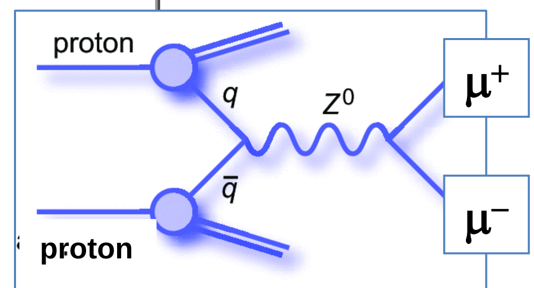


The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear “online”

2010

Data corre… …cted
→ re-discc… …el



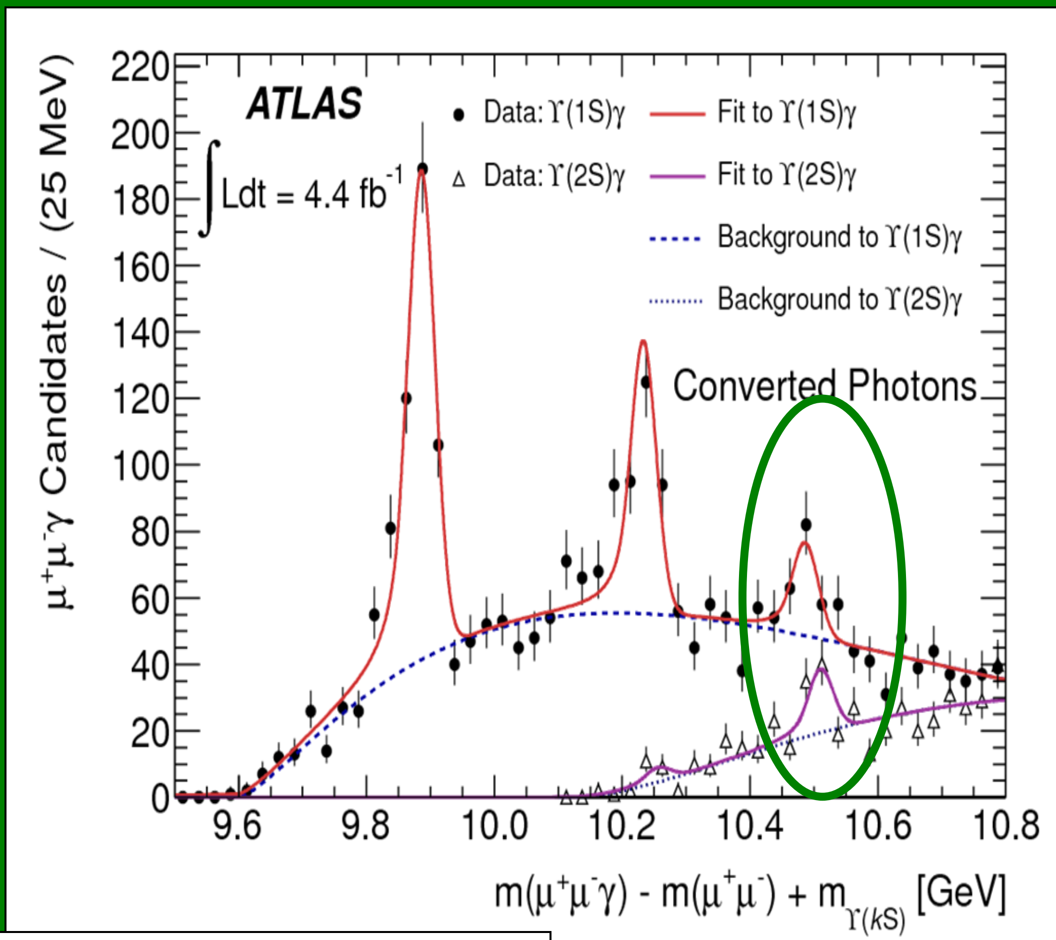


The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

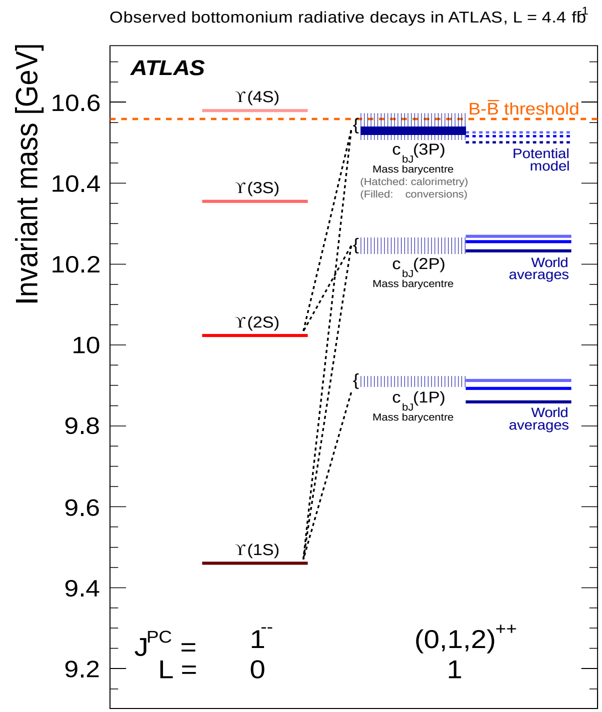
The first new particles 'discovered' at LHC, December 2011

$\chi_b(3P) \rightarrow \Upsilon(1s,2s)\ \gamma$

m [$\chi_b(3P)$] =10.530 ± 0.005 (stat) ± 0.009 (syst) GeV

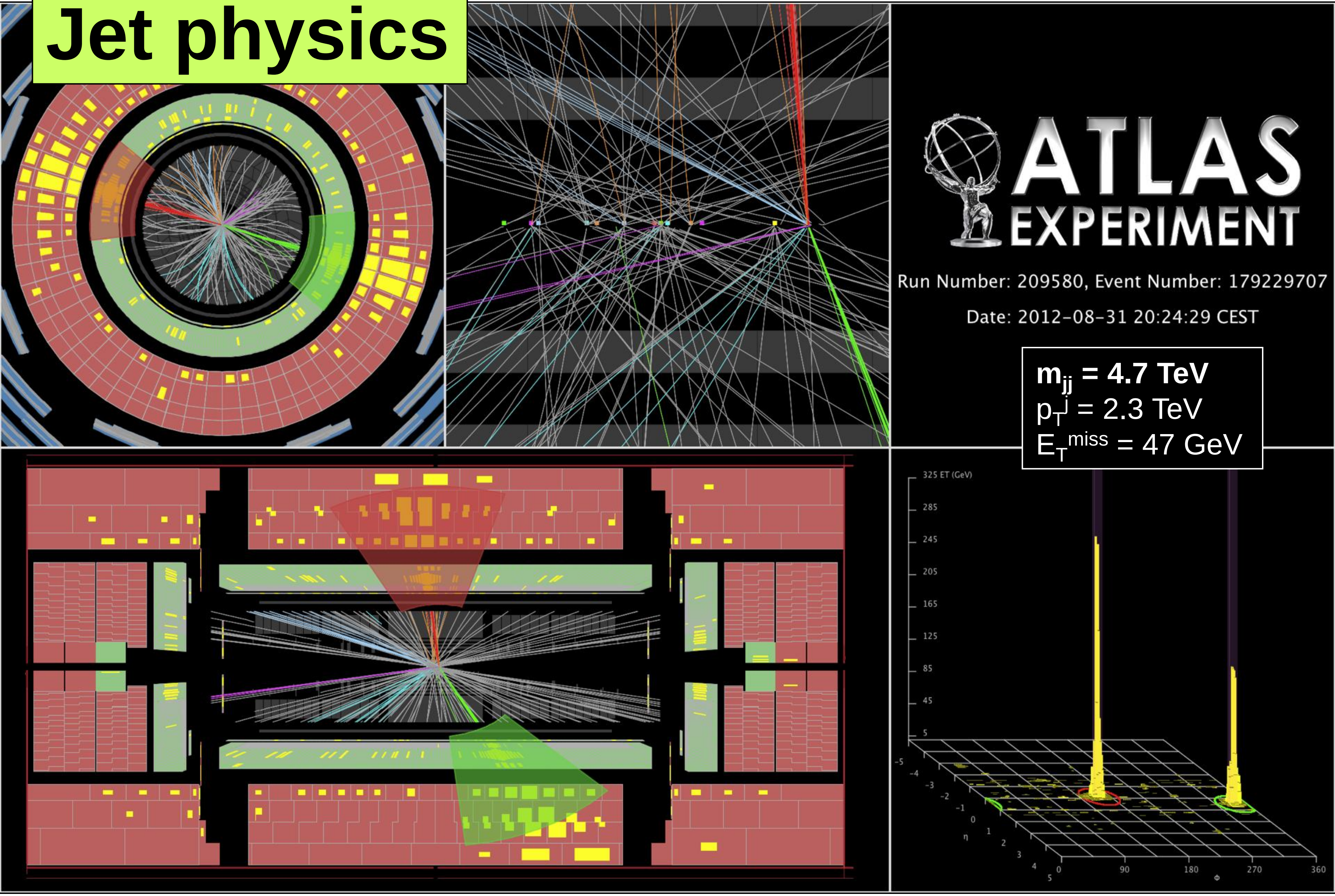


Phys. Rev. Lett. 108 (2012) 152001



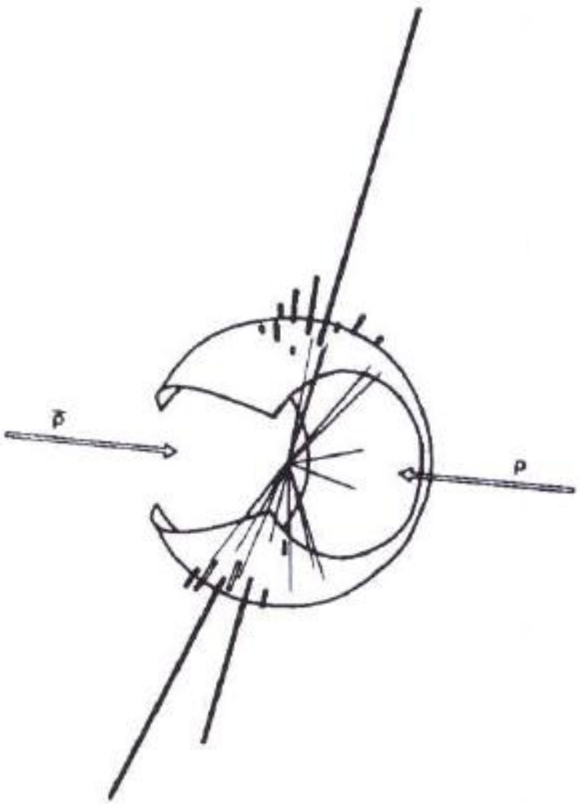
- $\chi_b(nP) \rightarrow \Upsilon(1s,2s)\ \gamma \rightarrow \mu\mu\ \gamma$
- $X_b(1P)$ m= 9.9 GeV and $X_b(2P)$ m= 10.2 GeV states clearly visible
- New structure at 10.5 GeV $\rightarrow X_b(3P)$
- Significance > 6 σ
- As theoretically predicted

Jet physics

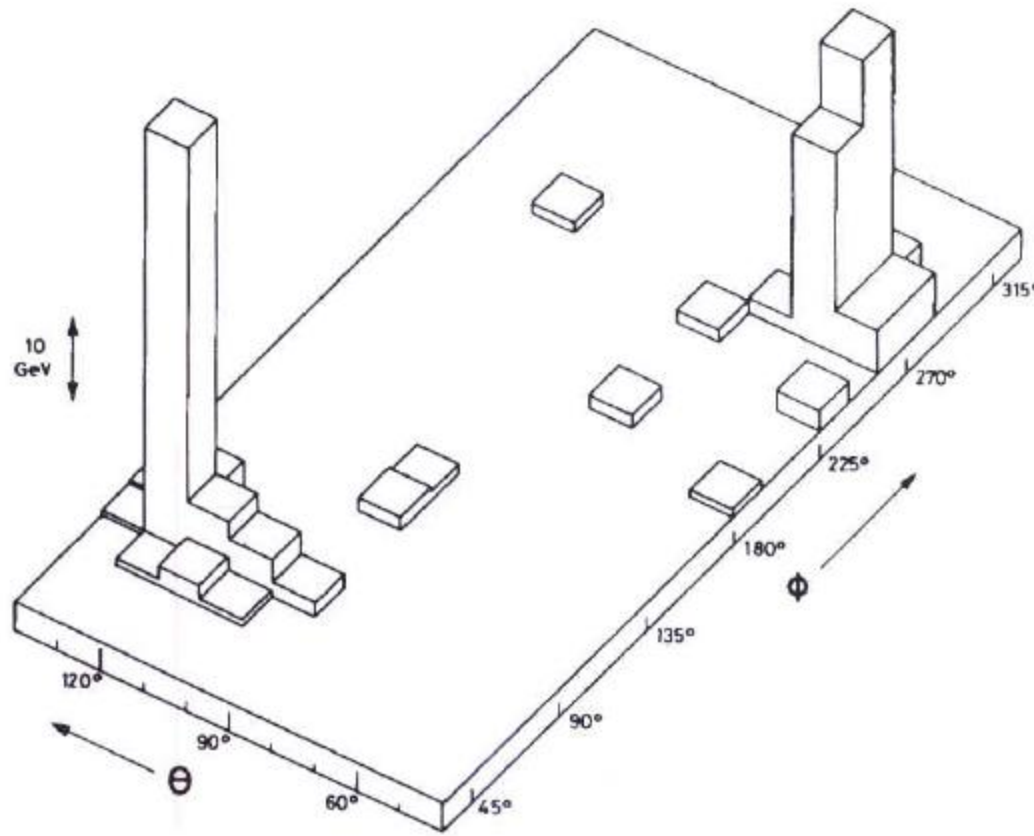

ATLAS EXPERIMENT
Run Number: 209580, Event Number: 179229707
Date: 2012-08-31 20:24:29 CEST
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …

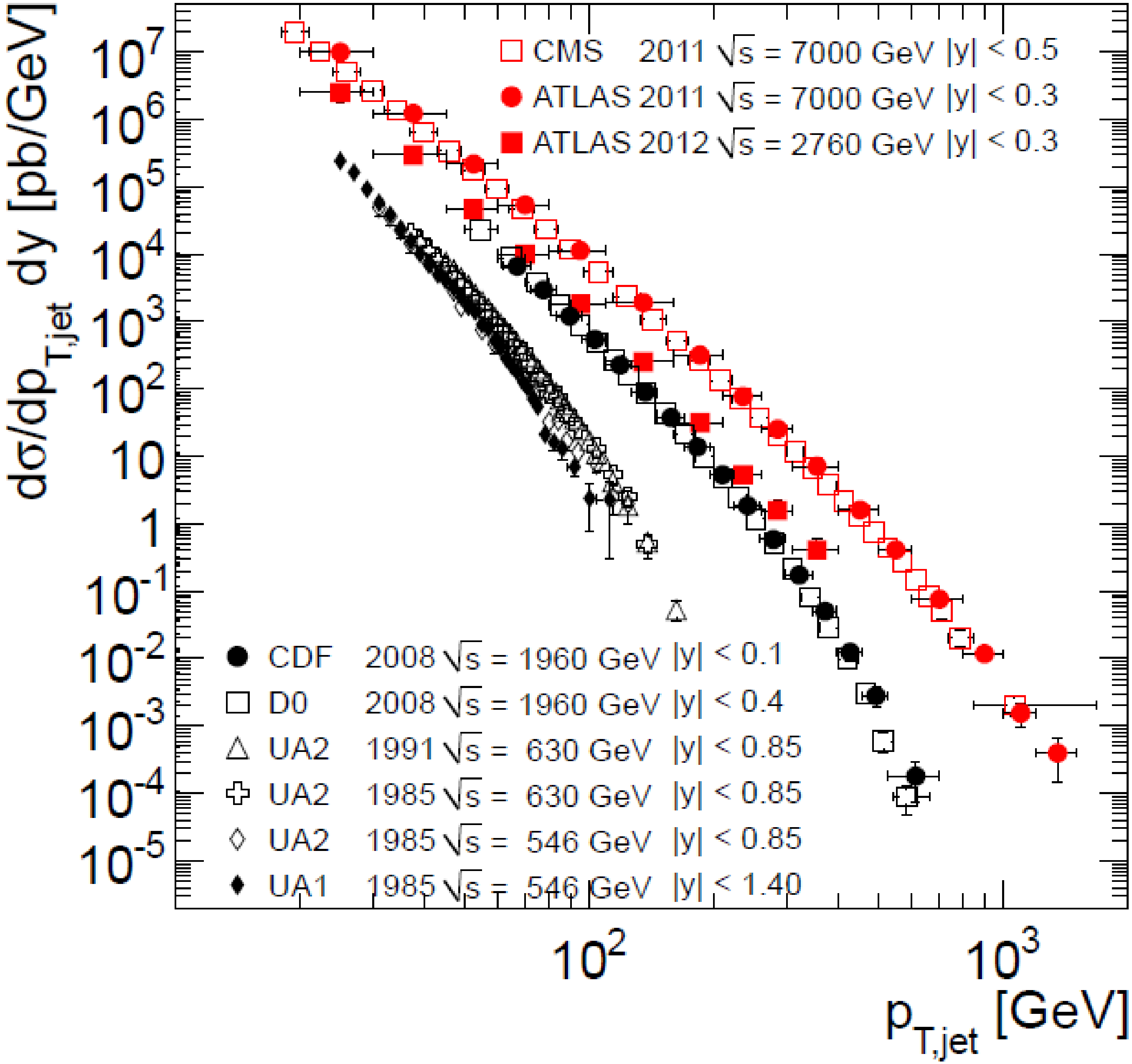
Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982



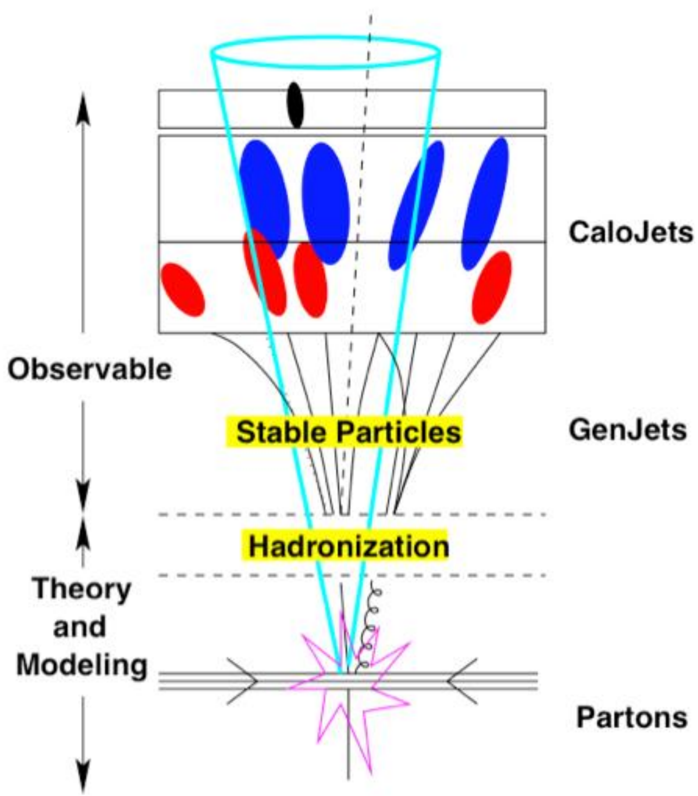
(a)

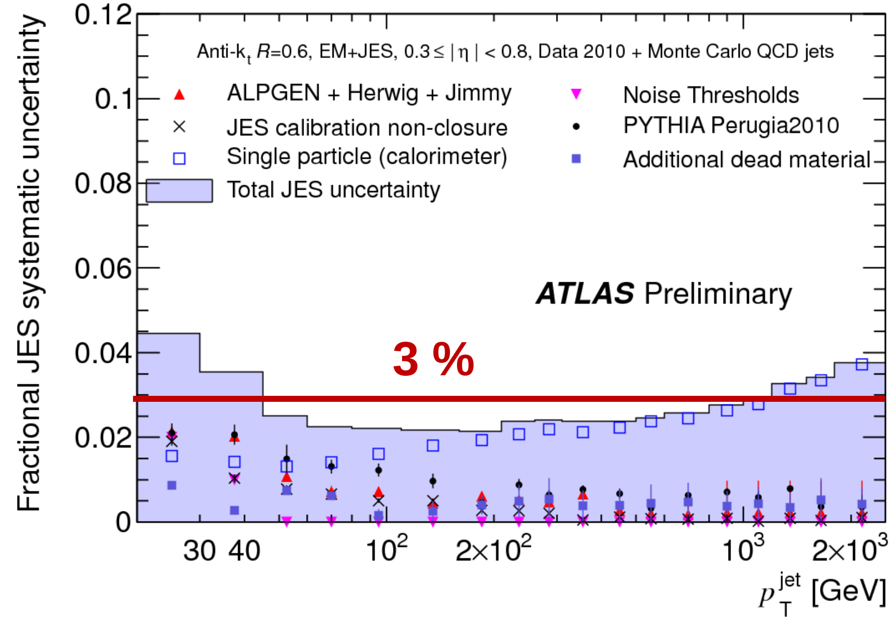


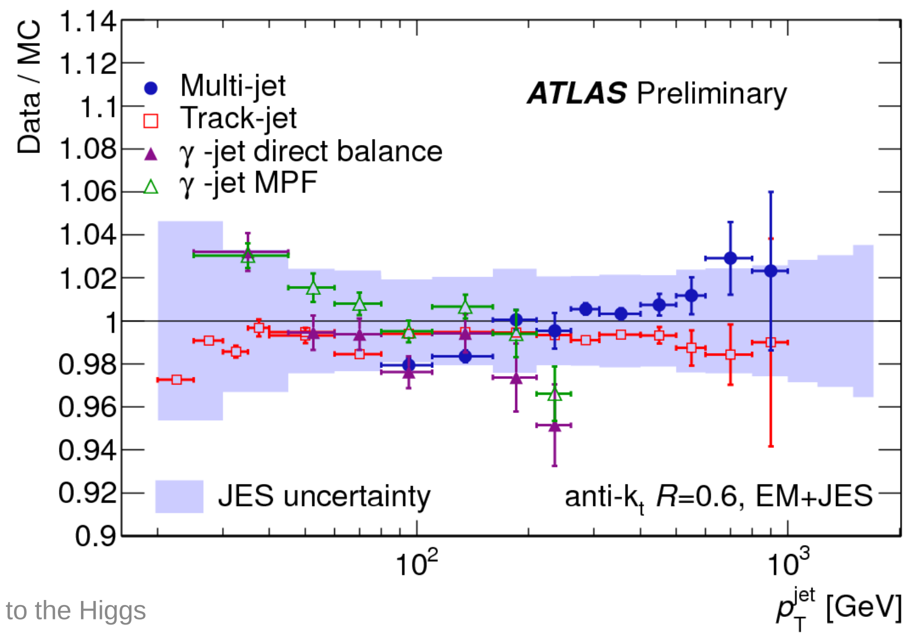
(b)


CMS 2011 √s = 7000 GeV |y| < 0.5
ATLAS 2011 √s = 7000 GeV |y| < 0.3
ATLAS 2012 √s = 2760 GeV |y| < 0.3
CDF 2008 √s = 1960 GeV |y| < 0.1
D0 2008 √s = 1960 GeV |y| < 0.4
UA2 1991 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 546 GeV |y| < 0.85
UA1 1985 √s = 546 GeV |y| < 1.40
dσ/dp_T,jet dy [pb/GeV]
p_T,jet [GeV]

A considerable effort went into understanding the Jet Energy Scale (JES), the dominant source of uncertainties for most jet measurements



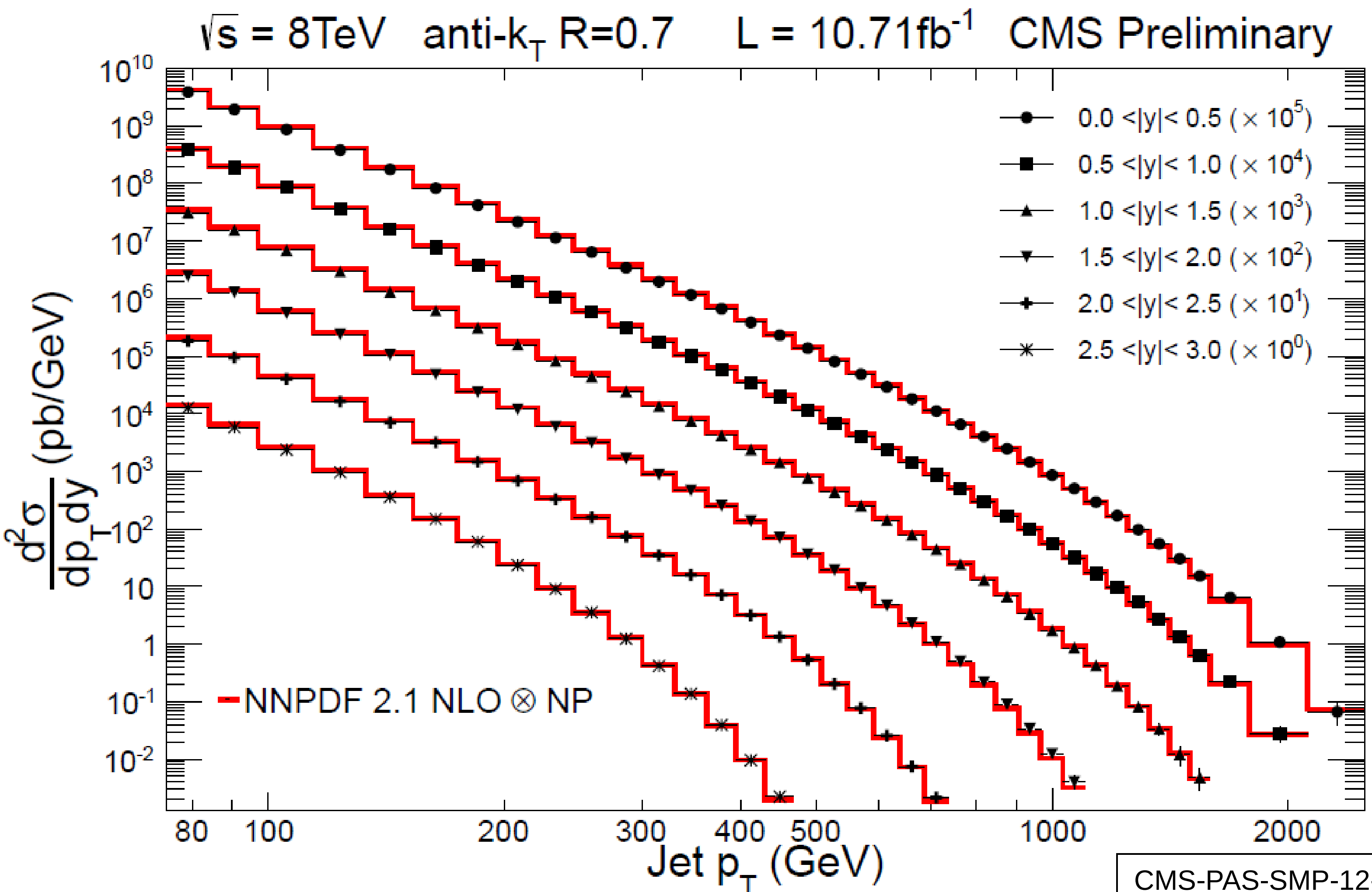




ATLAS-CONF-2011-032 and arXiv:1112.6426v1[hep-ex]
Updated detailed results: Eur. Phys. J. C75 (2015) 17

Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

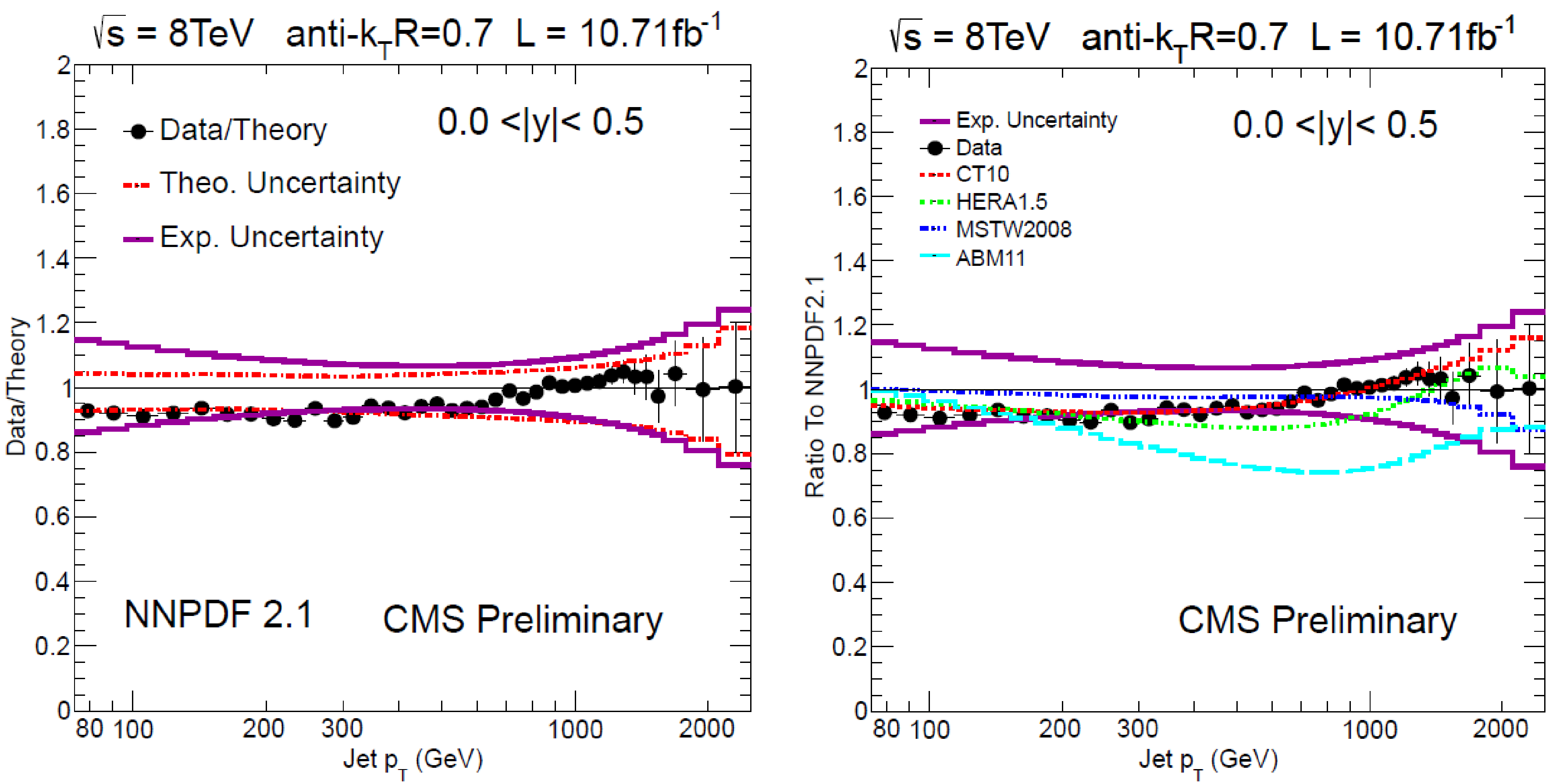
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins



CMS-PAS-SMP-12-012

Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

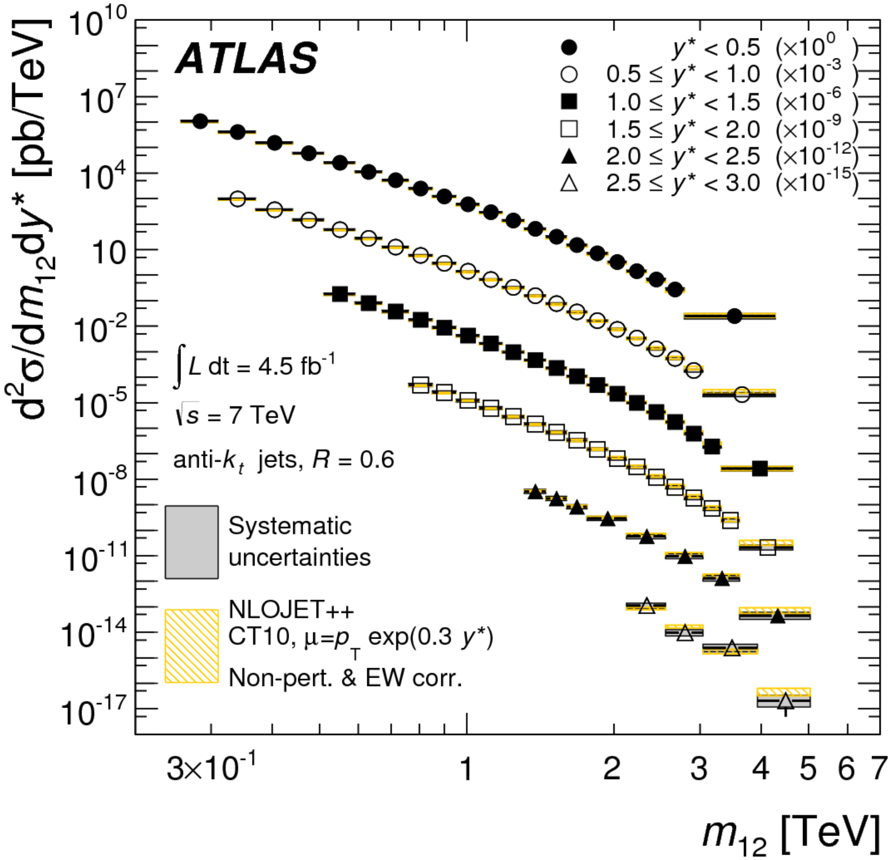
Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins

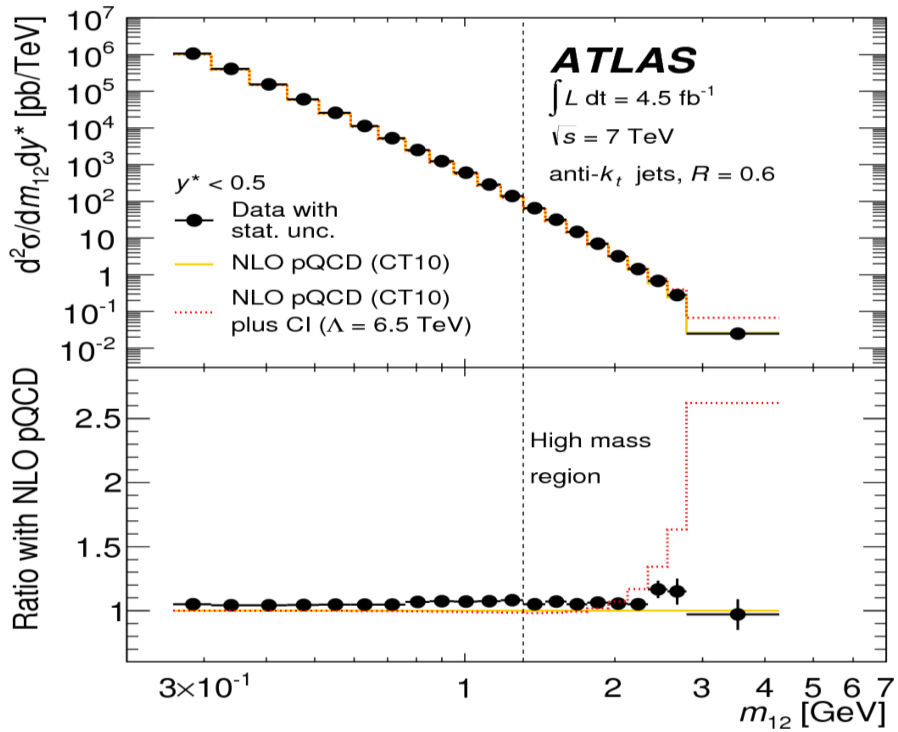


CMS-PAS-SMP-12-012

Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example: The di- jet cross sections as a function of the jet P_T in rapidity bins

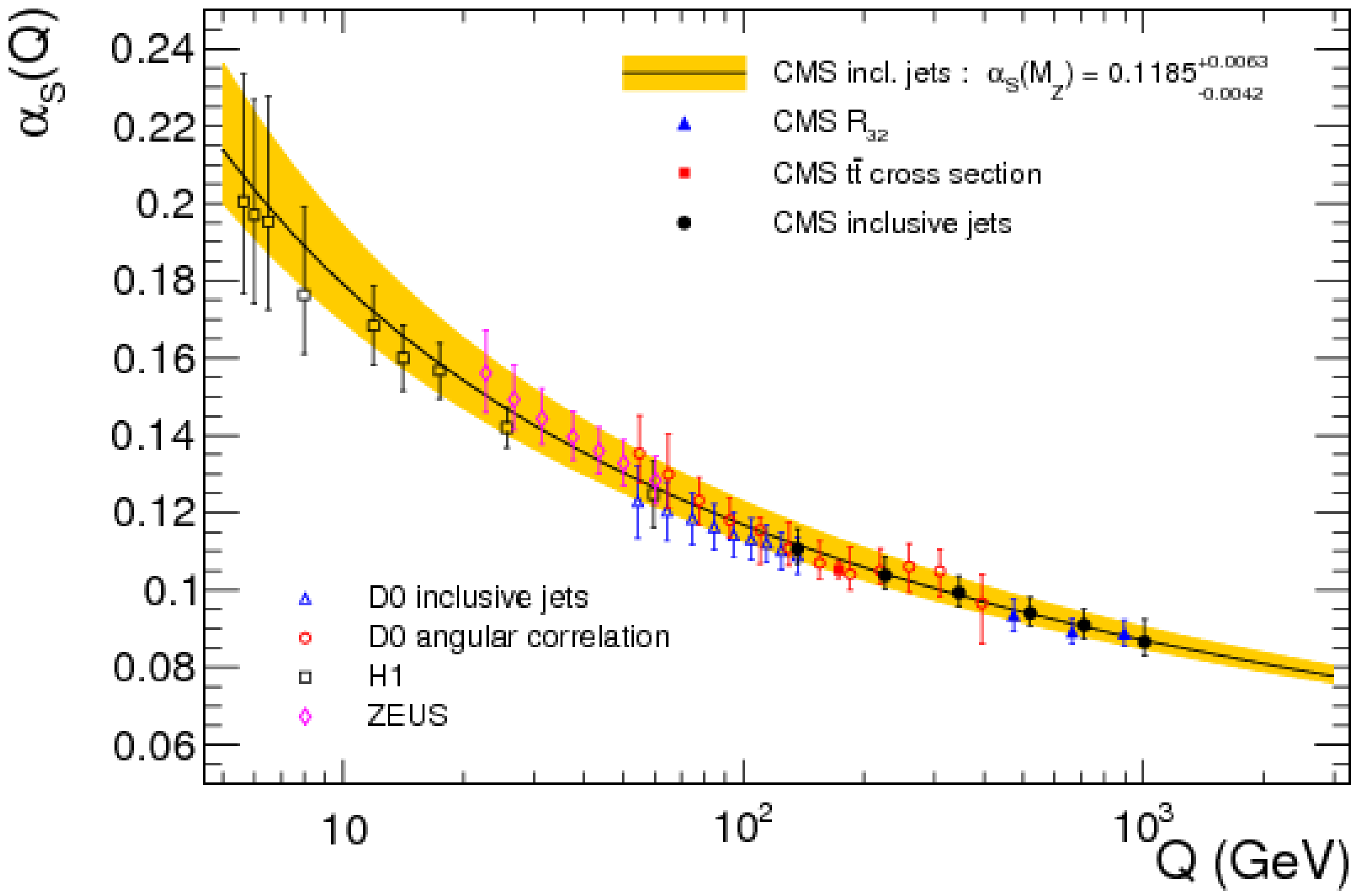




Deviations from QCD at large p_T could hint at substructure inside the quarks (remember the famous Rutherford scattering ~ 100 years ago)

JHEP 05 (2014) 059

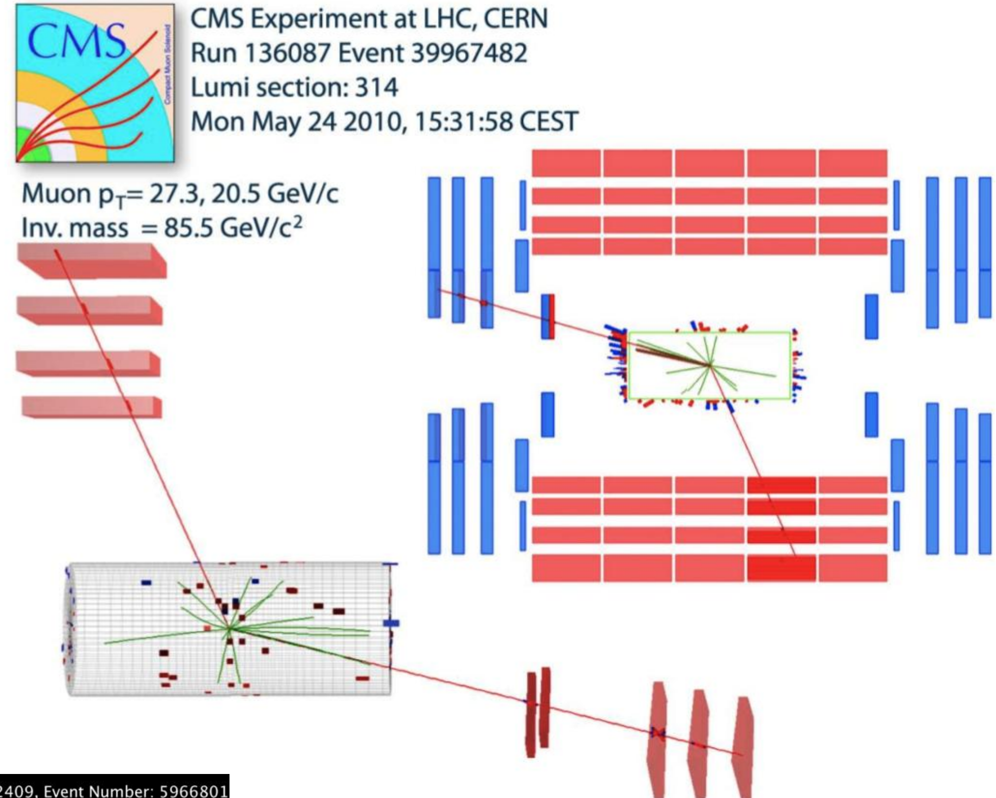
The running strong coupling $\alpha_s(Q)$



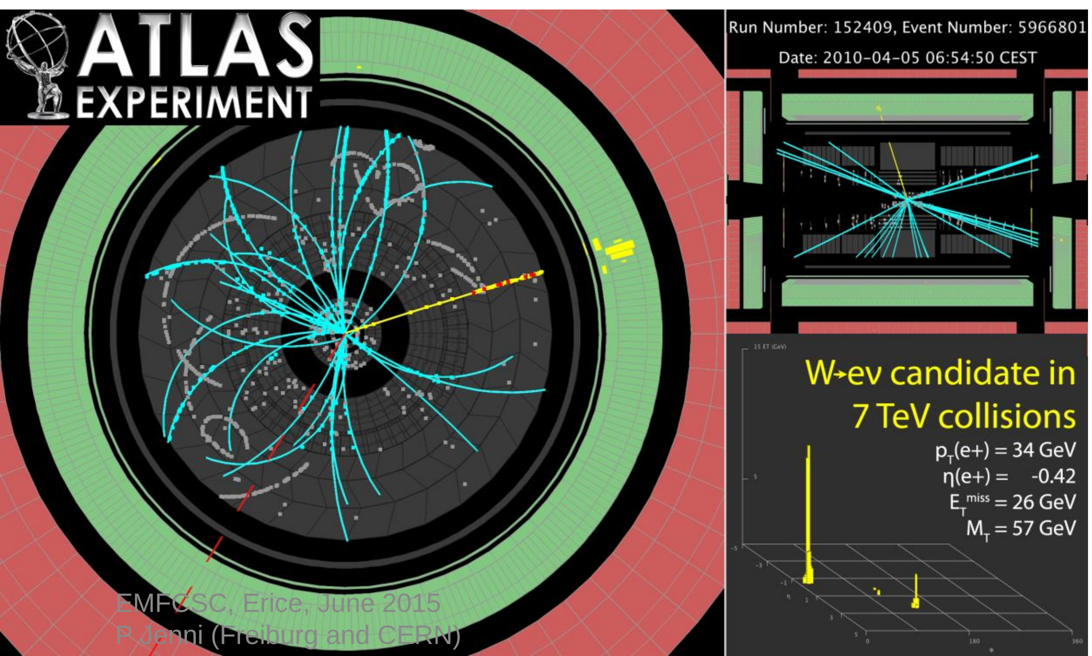
arXiv:1410.6765[hep-ex] sub. to Eur. Phys. J. C

Standard Model Physics

Candidate Z → $\mu^+\mu^-$



W → eν candidate



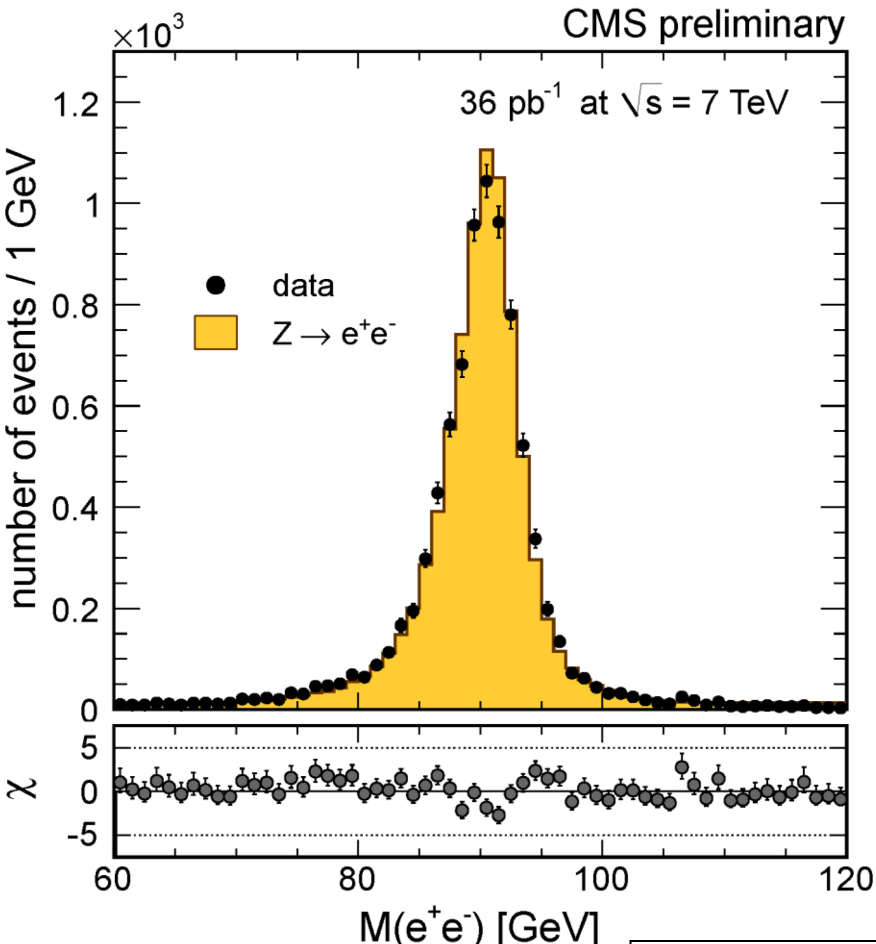
Today each ATLAS and CMS have in their data more than:

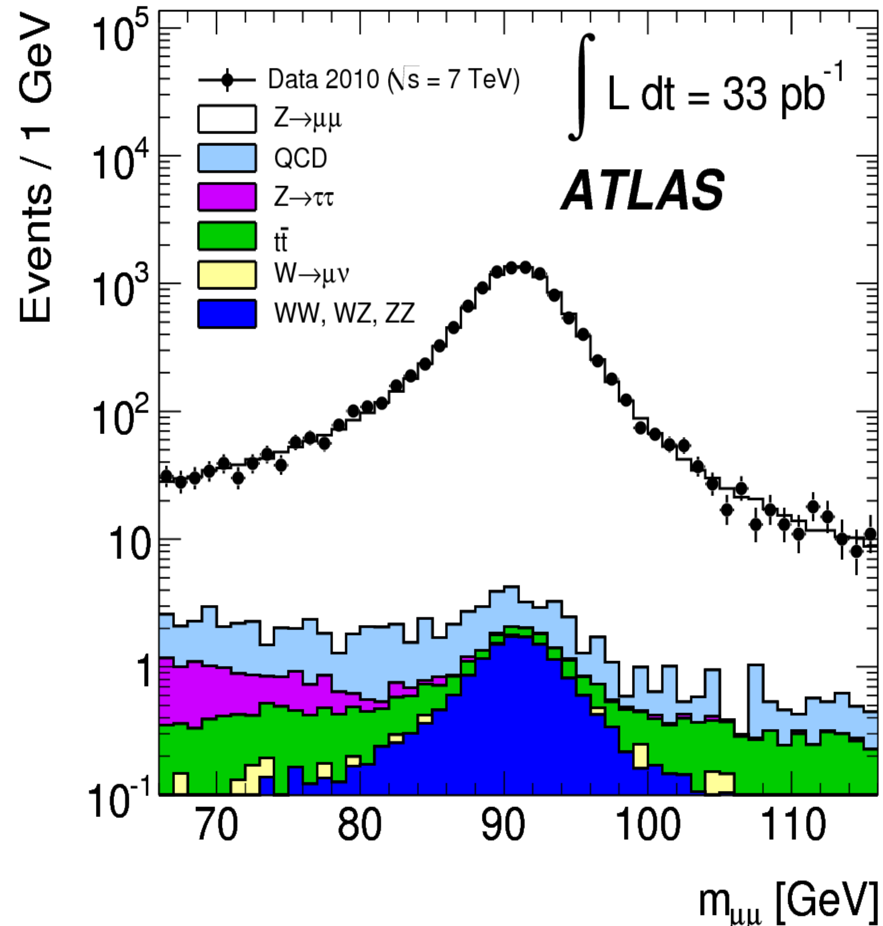
100 M W→ μν, eν events
10 M Z → μμ, ee events

after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004





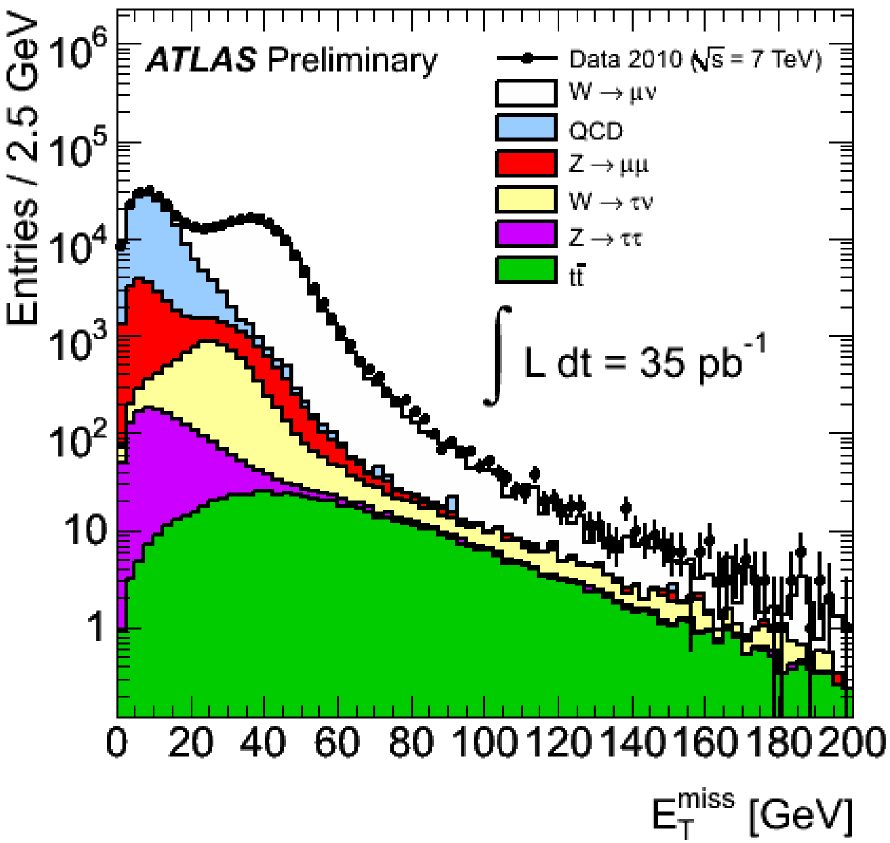
JHEP 10 (2011) 132

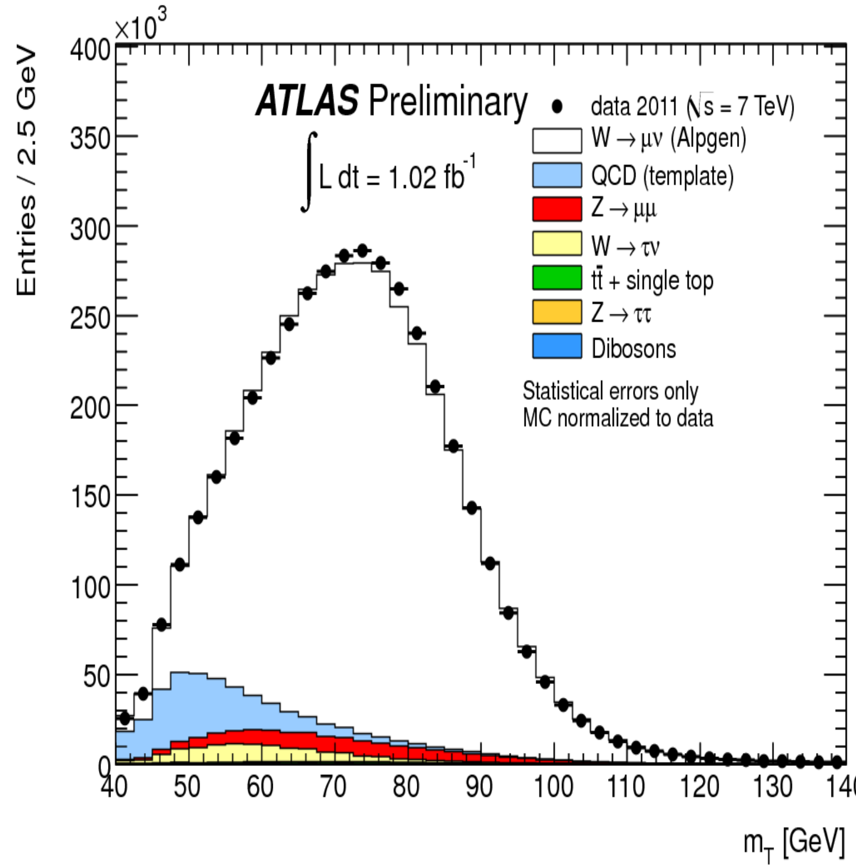
Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV





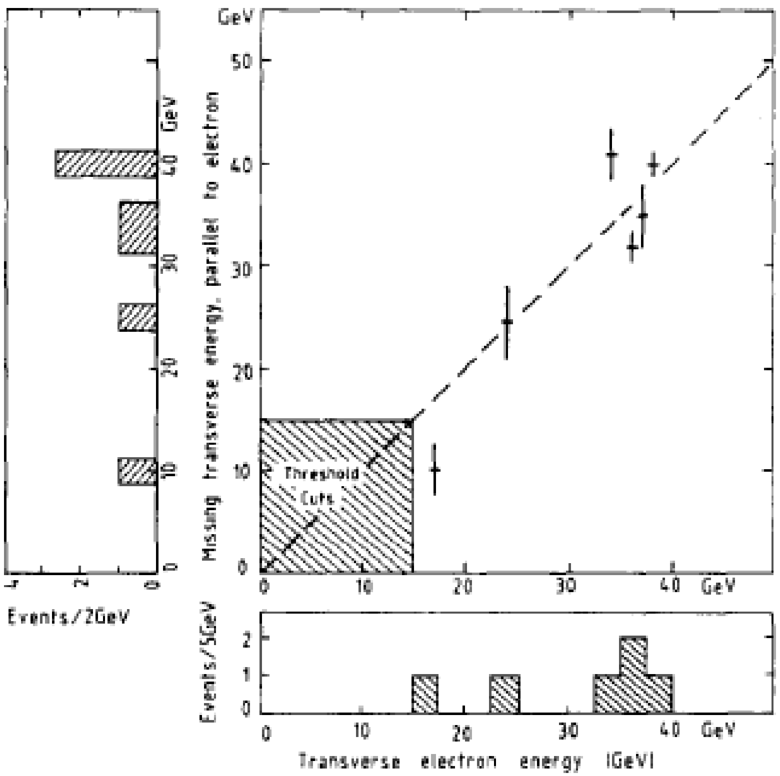
Missing transverse energy from the W → μ + ν decays

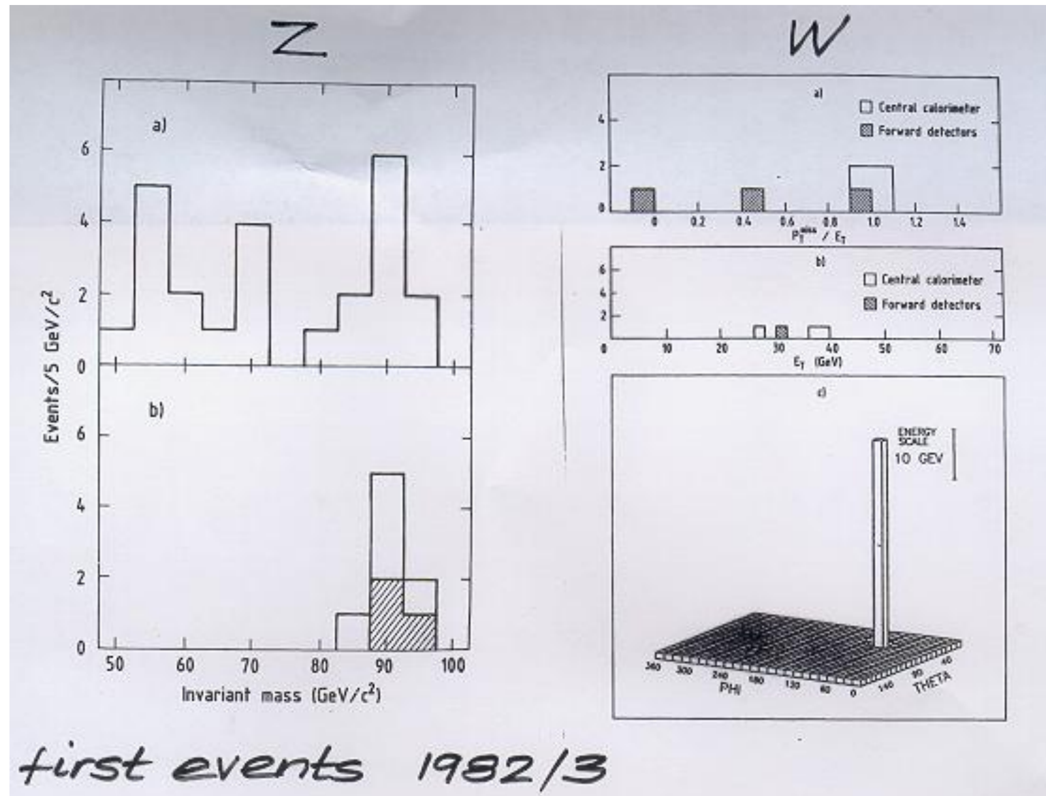
ATLAS-CONF-2011-041

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

What a contrast to the Intermediate Vector Boson discovery distributions in 1982 and 1983 by UA1 and UA2 with just a few events …

Some 30 years ago!

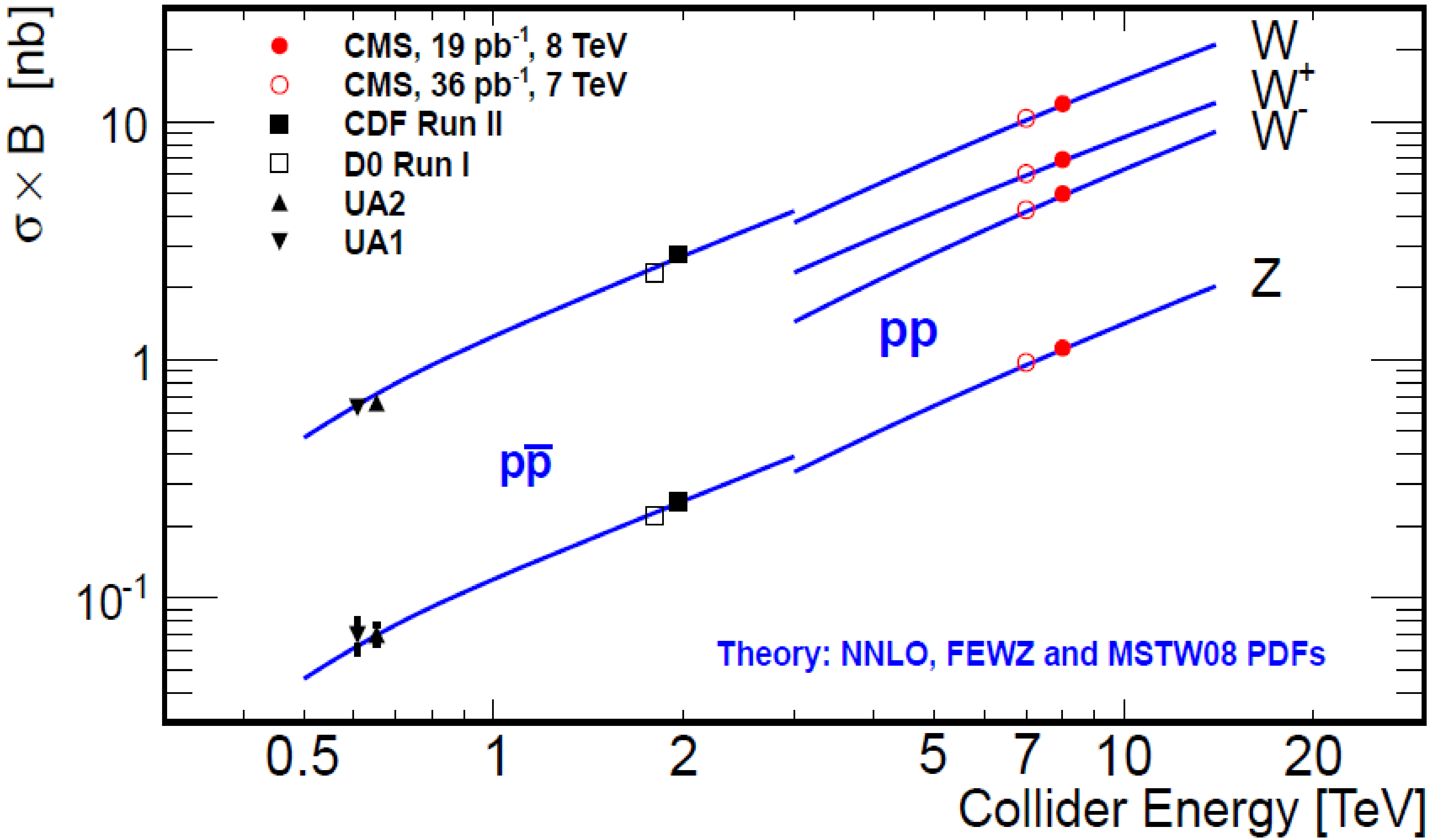




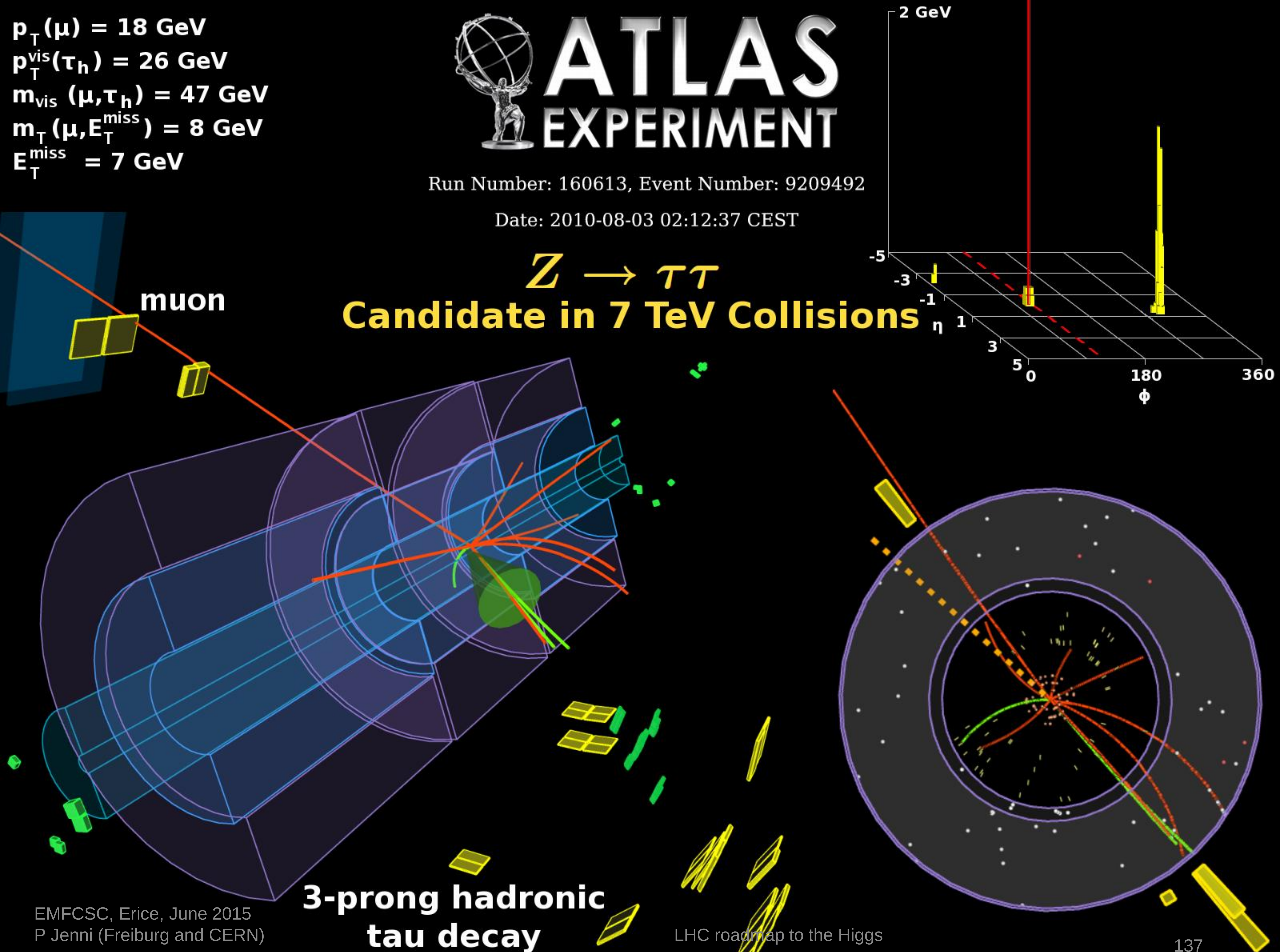
The UA1 W → eν events

The UA2 distributions

Cross section measurements

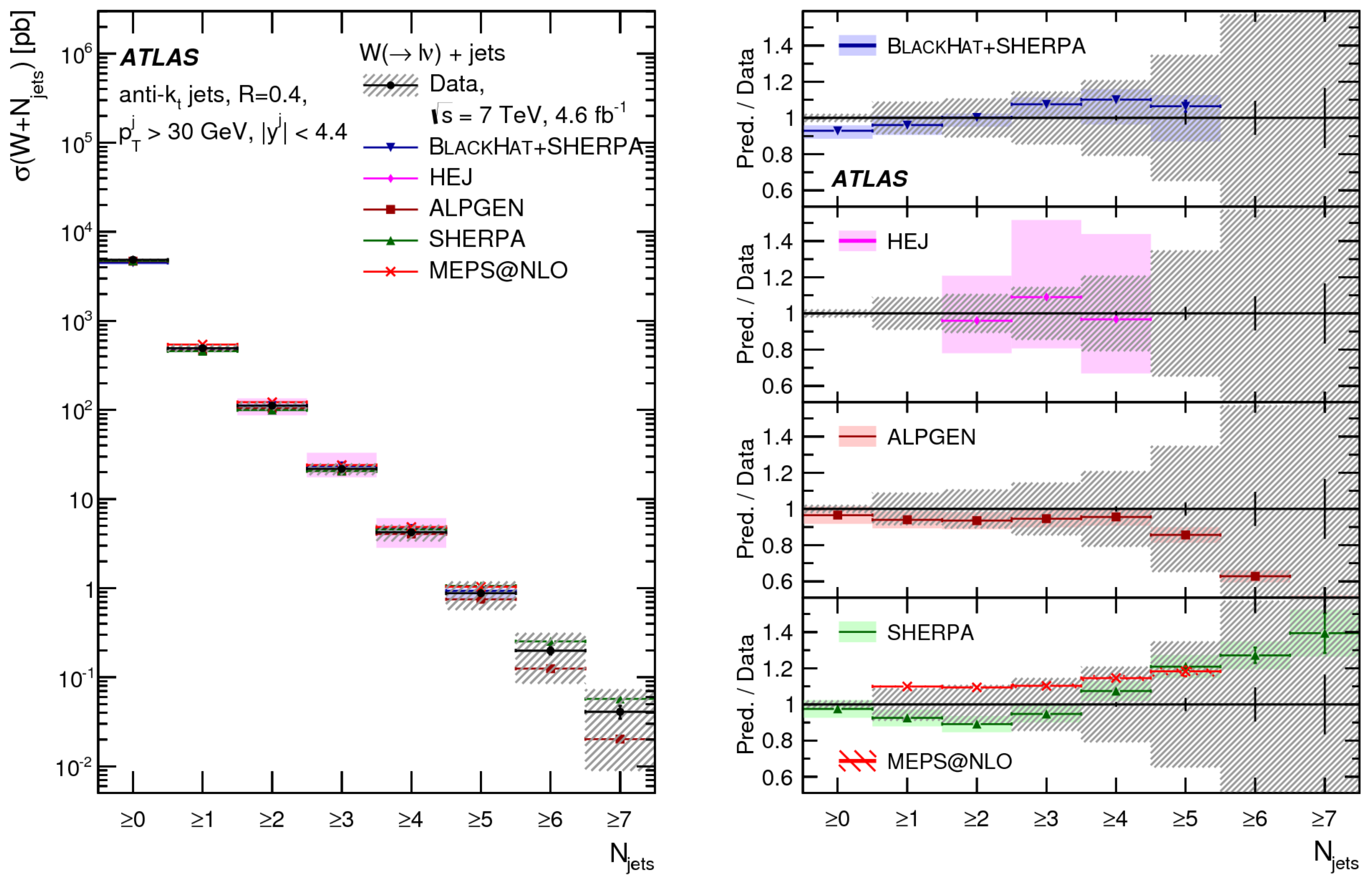


CMS-PAS-SMP-12-011


$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
2 GeV
η
-5
-3
-1
1
3
5
0
180
360
φ

W + jet(s) production

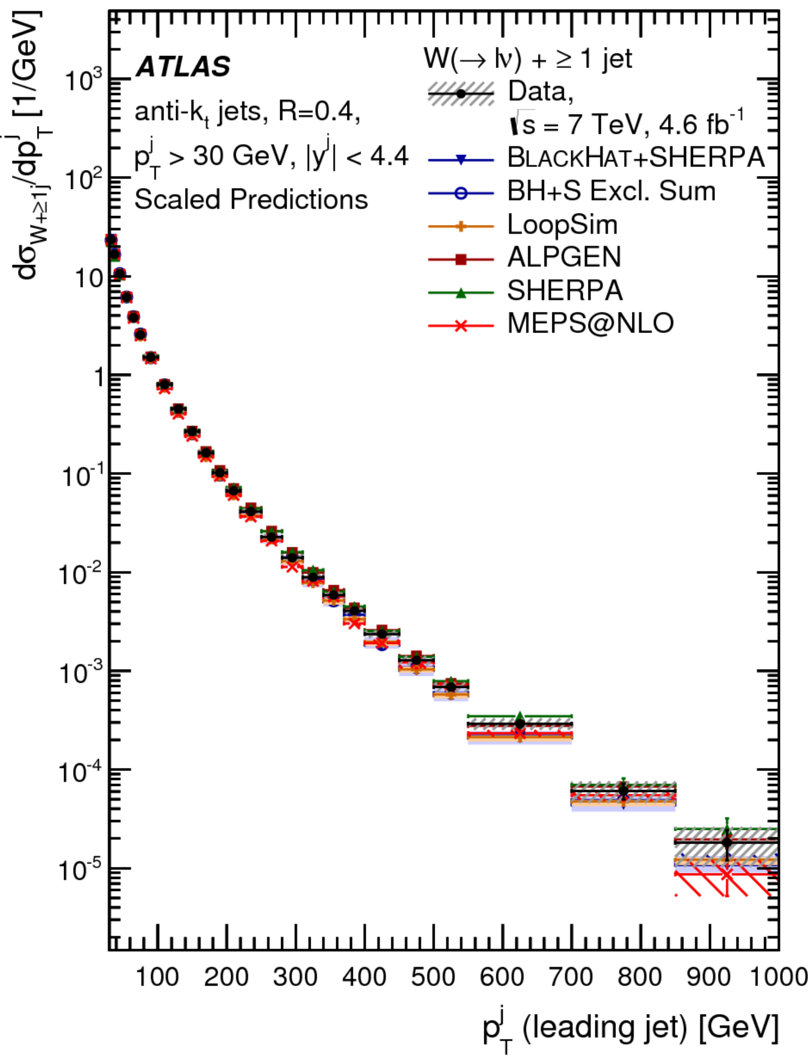
Both an interesting QCD measurement as well as a dominant background to many searches

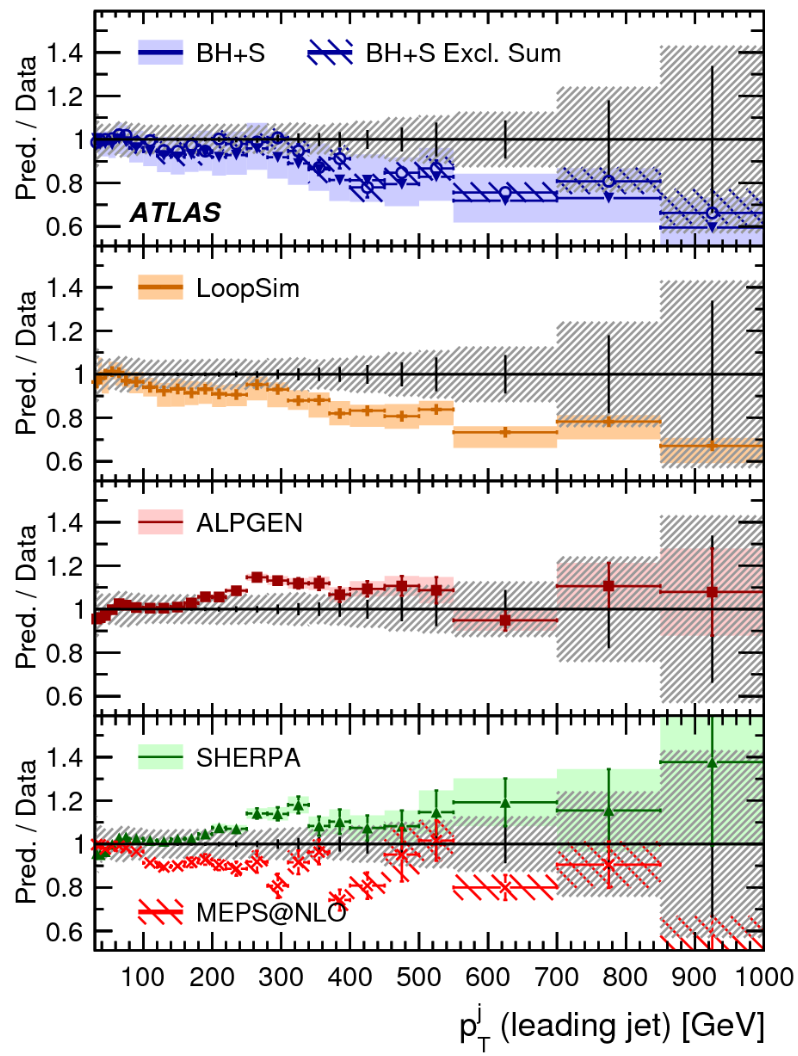


Euro. Phys. J. C 75 (2015) 82

W + jet(s) production

Both an interesting QCD measurement as well as a dominant background to many searches



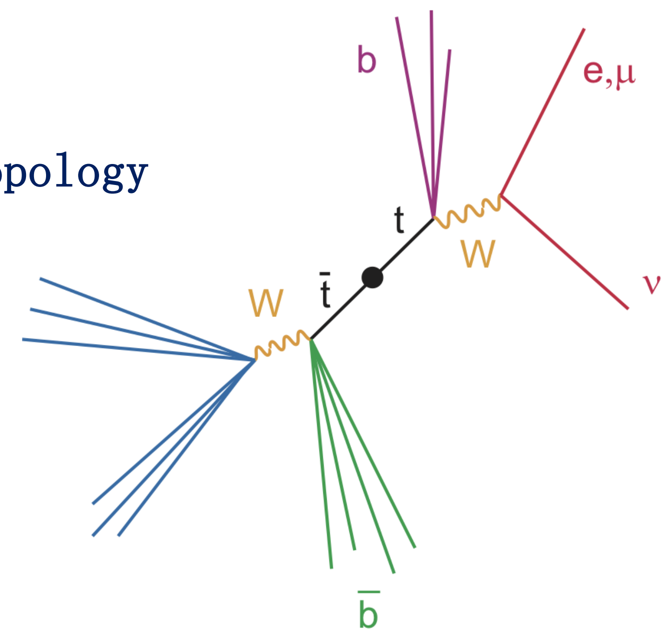


Euro. Phys. J. C 75 (2015) 82

Top measurements

- Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:
  - e, μ, E_T^{miss}, jets, b-tag

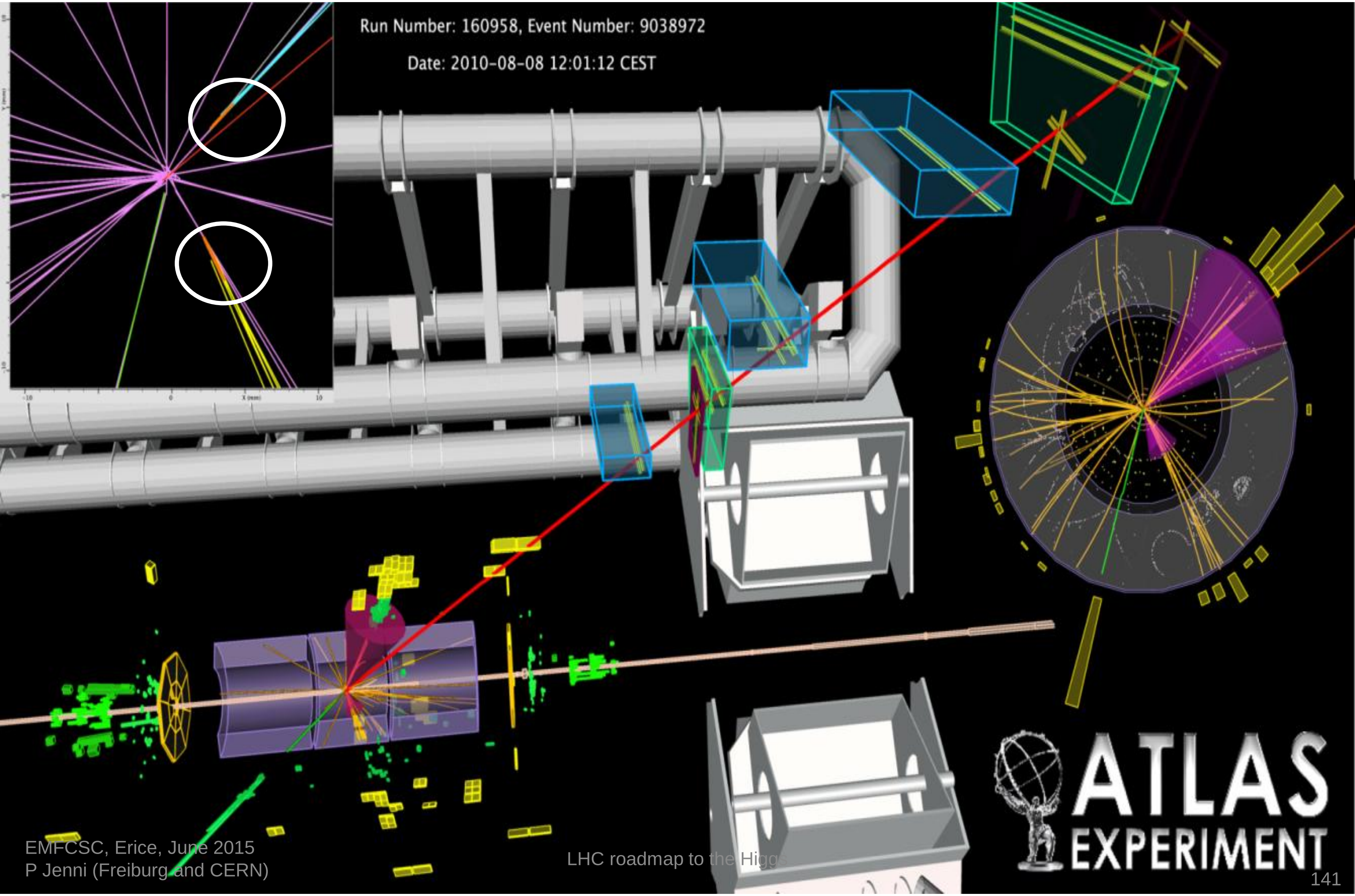
- Assume all tops decay to Wb: event topology then depends on the W decays:
  - one lepton (e or μ), E_T^{miss}, jjbb (37.9%)
  - di-lepton (ee, μμ or eμ), E_T^{miss}, bb (6.5%)



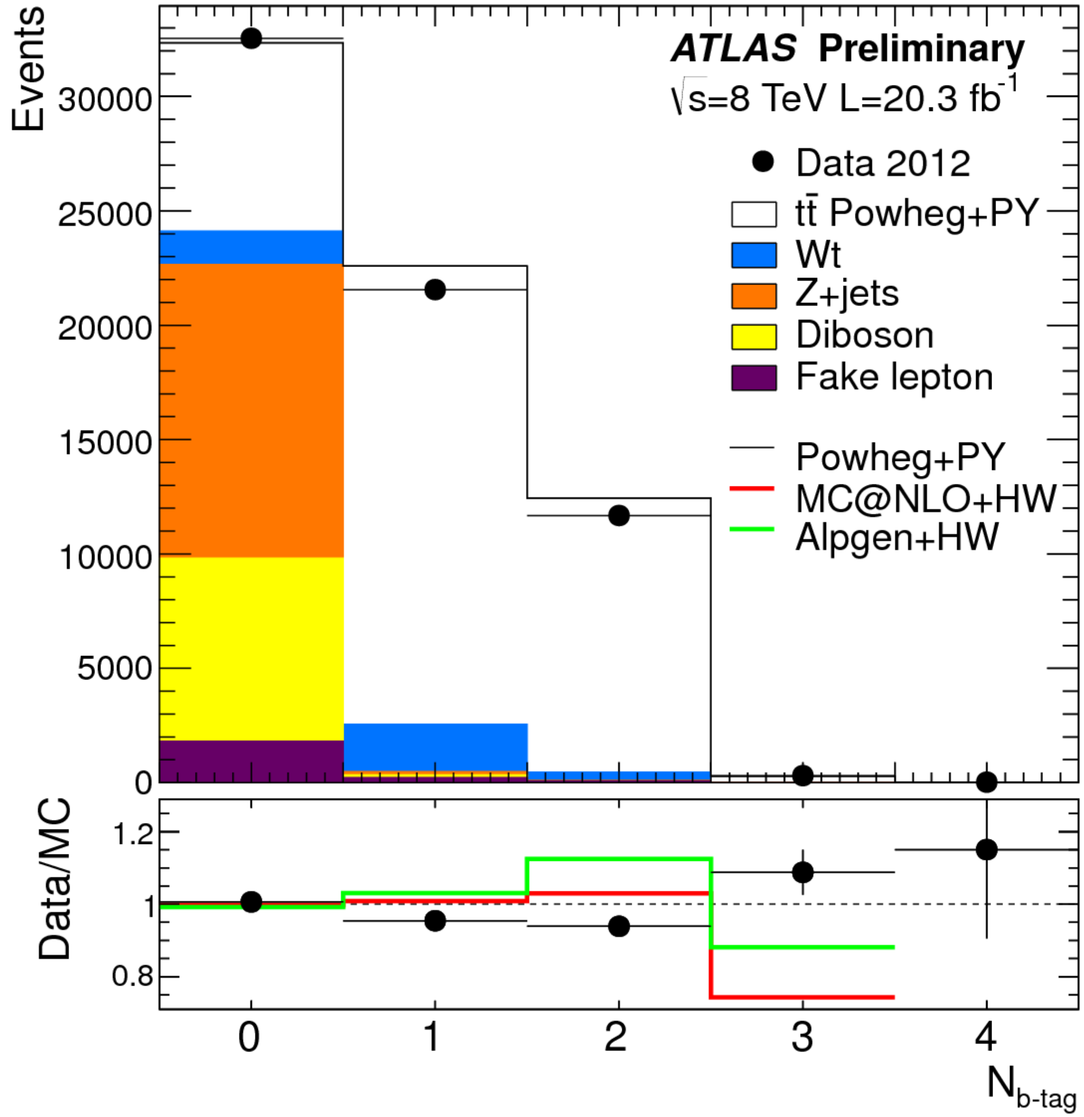
- Data-driven methods to control QCD and W+jets backgrounds

$t\bar{t}$ candidate event

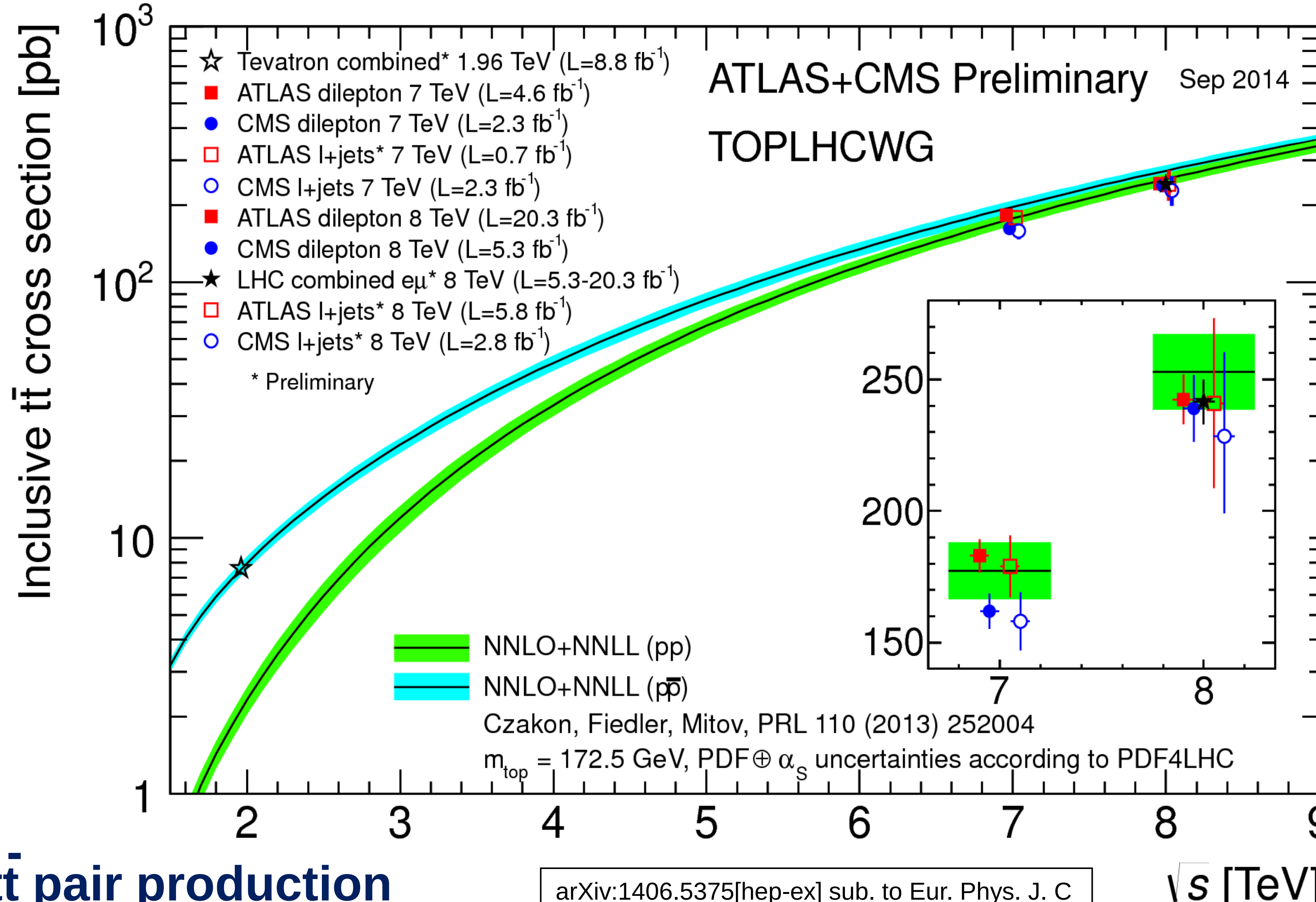
e + μ + 2 jets (b-tagged) +ETmiss



$t\bar{t}$ – production with b-tagged e-μ events



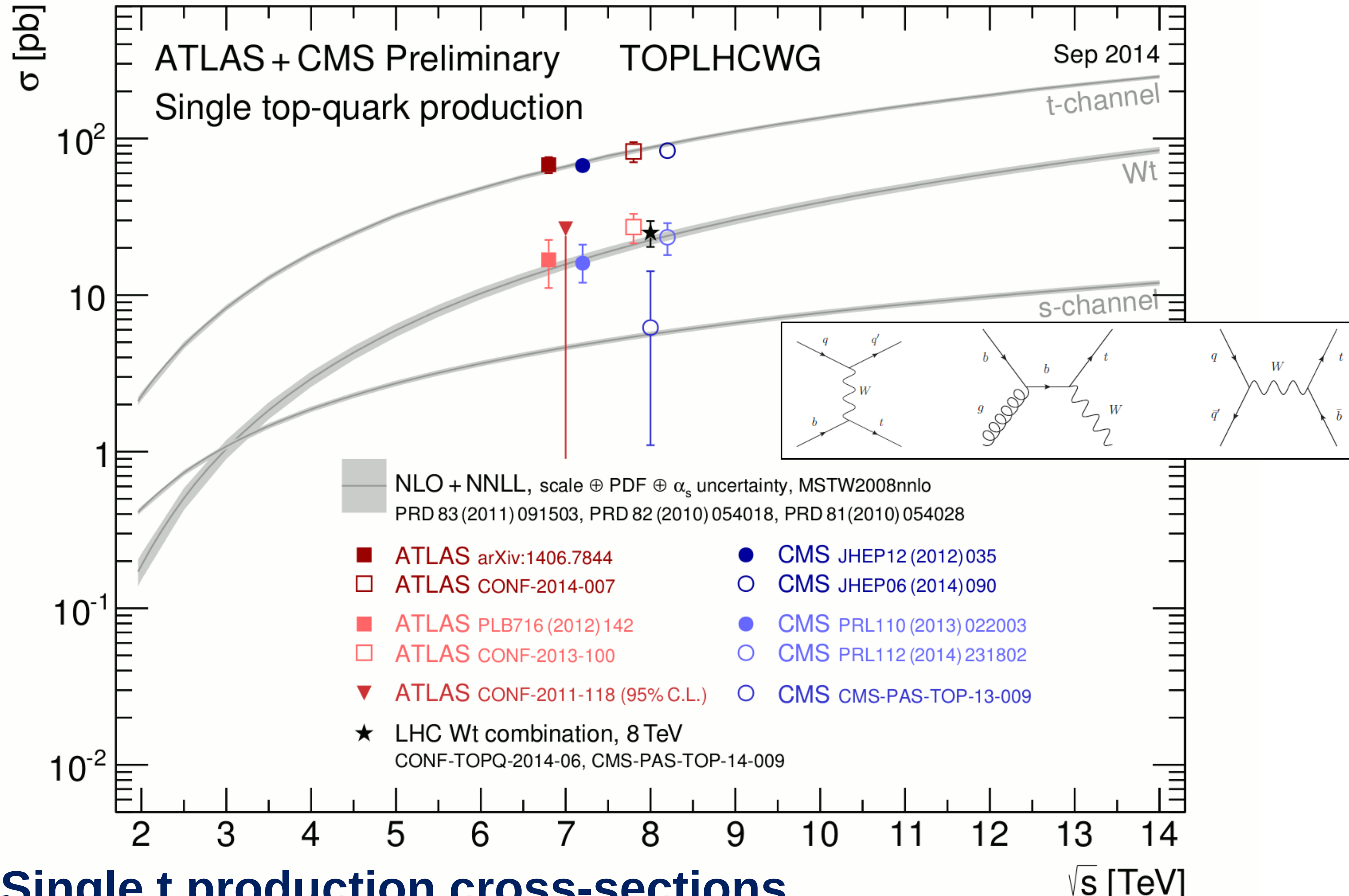
ATLAS-CONF-2013-097



$t\bar{t}$ pair production cross-sections

arXiv:1406.5375[hep-ex] sub. to Eur. Phys. J. C

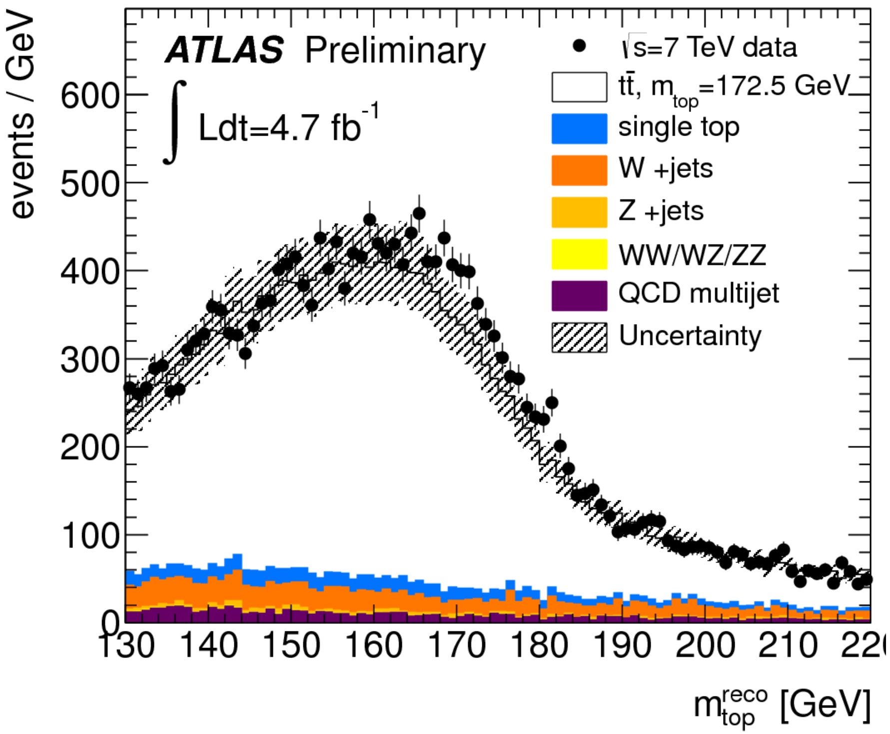
JHEP 02 (2014) 024

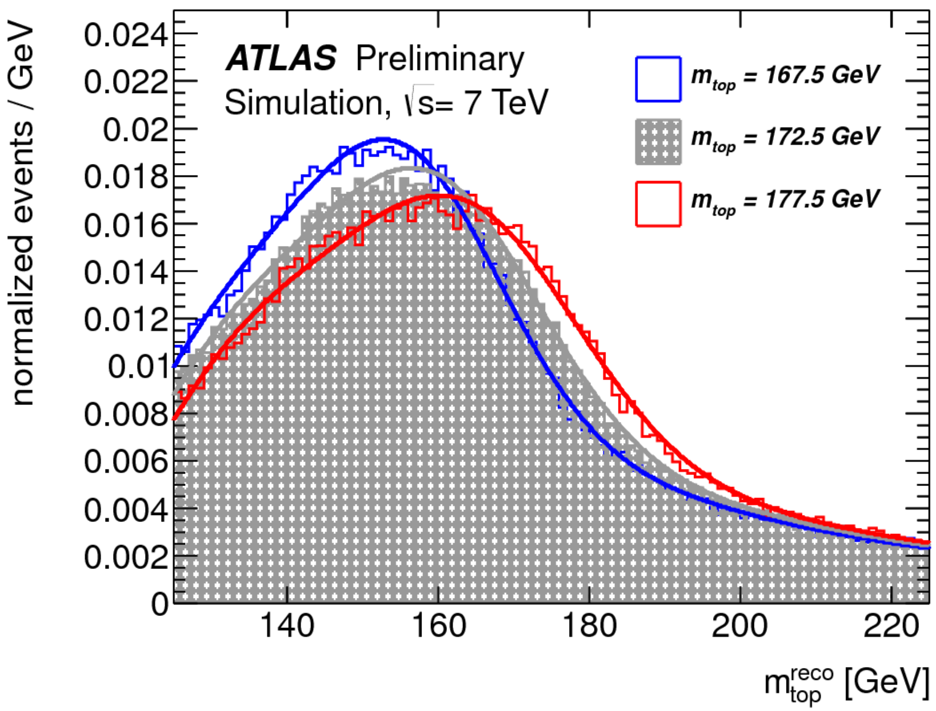


Single t production cross-sections

Example of top mass measurement: templates in the lepton-jet final state channel

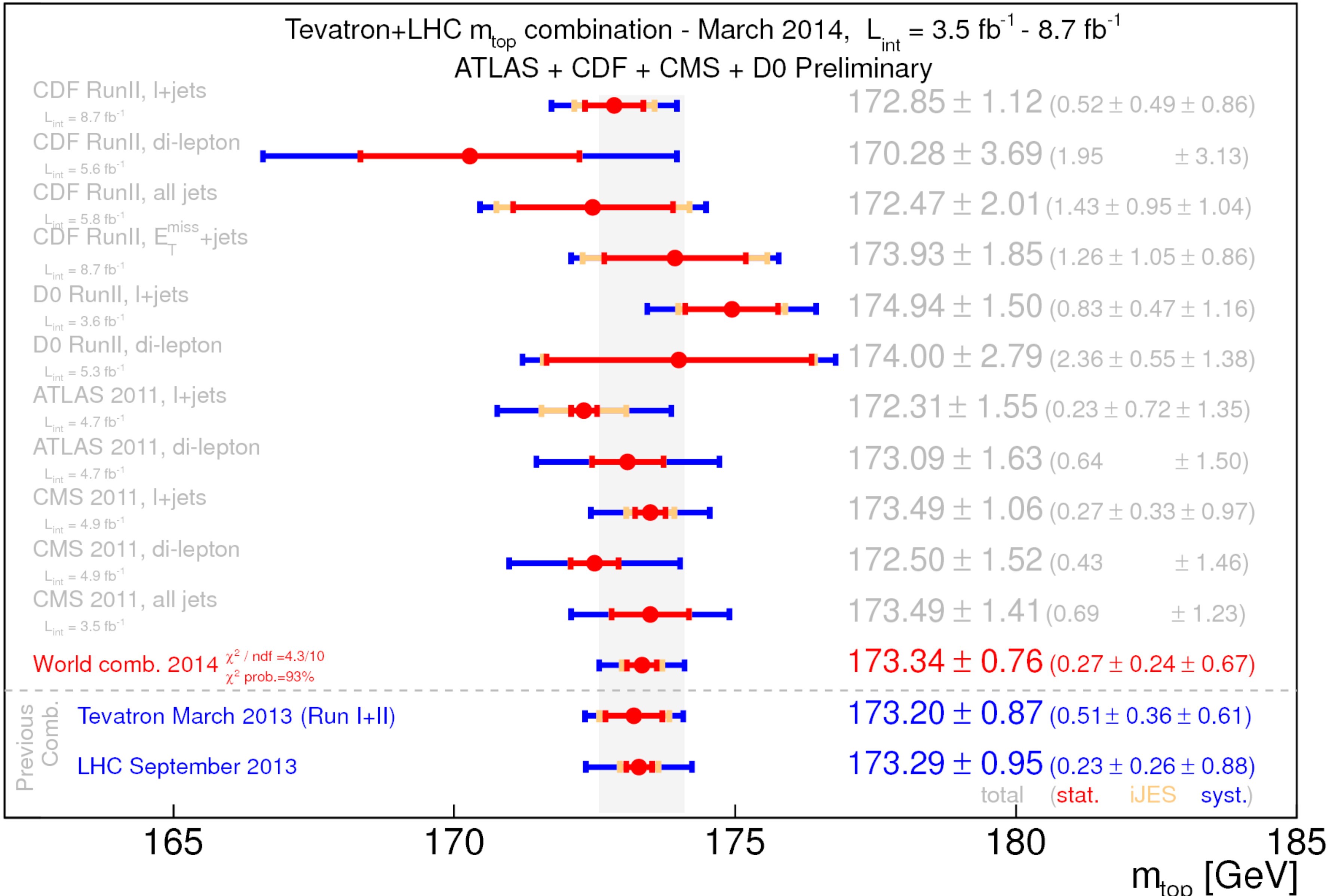
ATLAS-CONF-2013-046

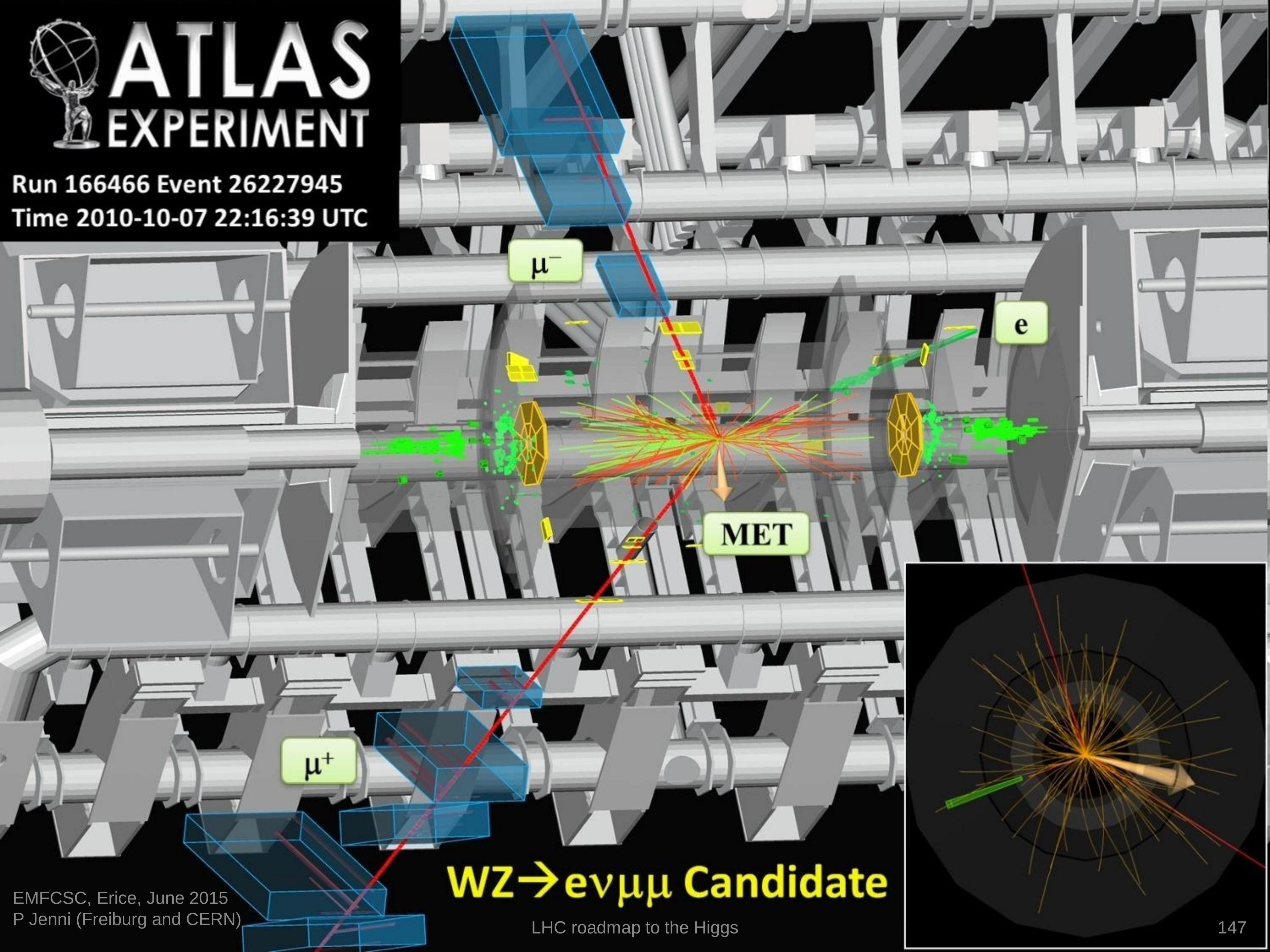




Mass is determined from a likelihood fit taking into account all measured kinematical variables

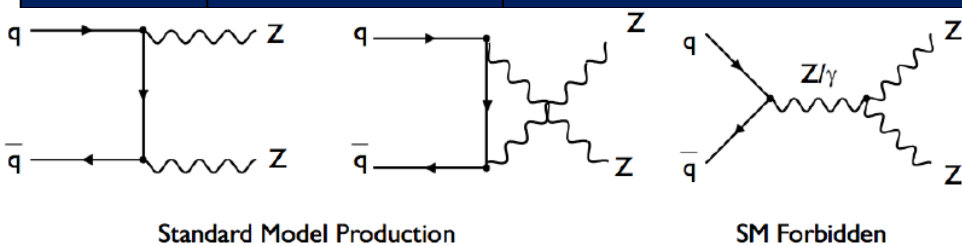
t mass determinations March 2014 (not including some more recent results)



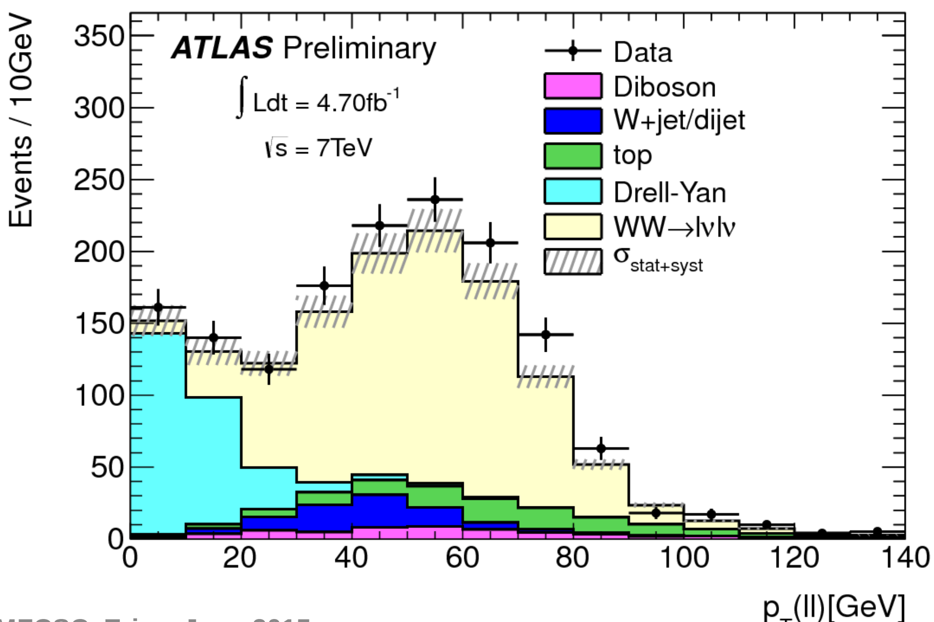

ATLAS EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

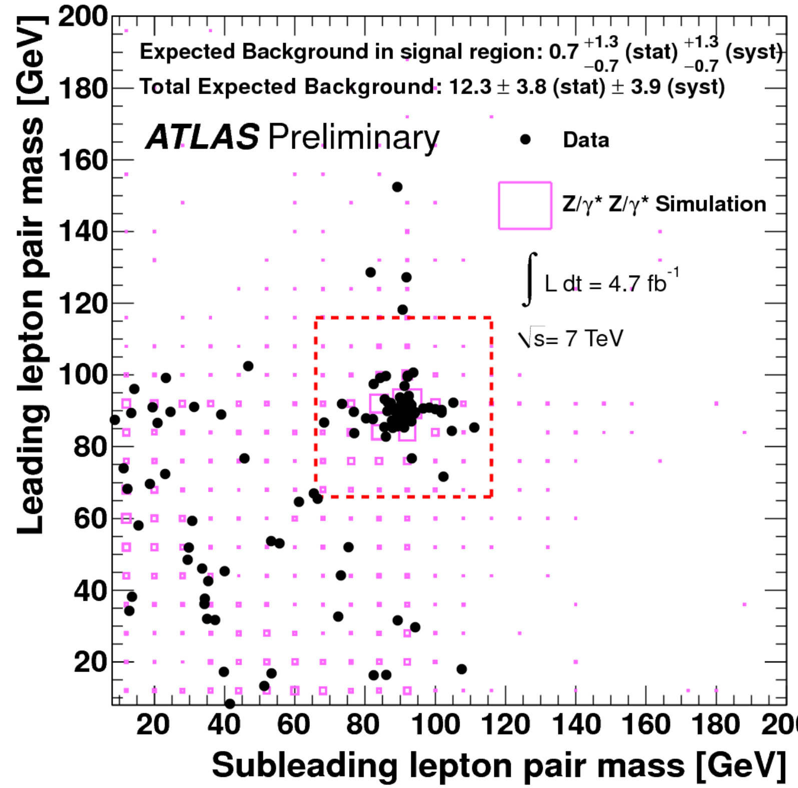
Electroweak di-boson production

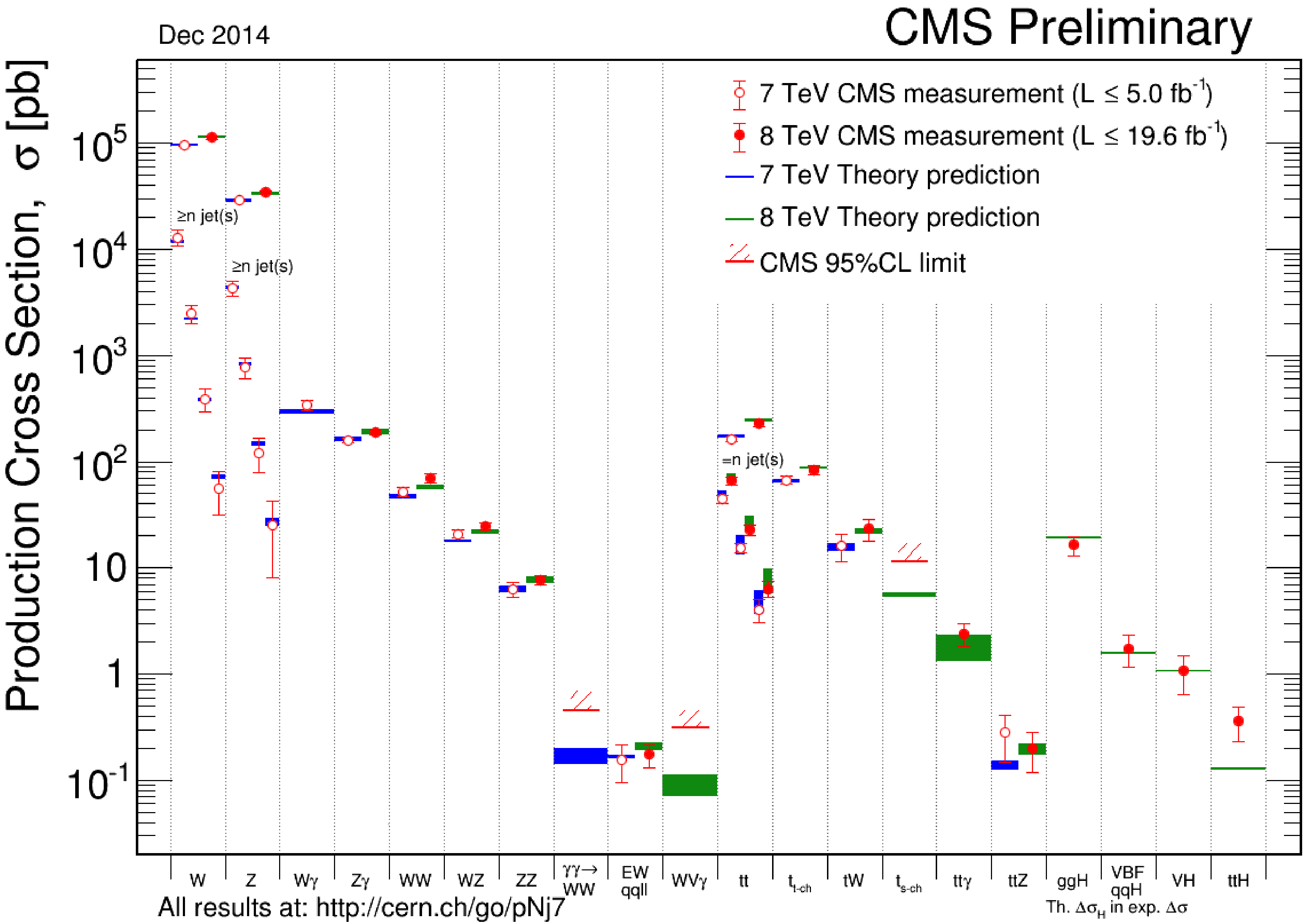
Process	Final state	Measured total cross-section	Theory (NLO SM)
WW	$l\nu l\nu$	$\sigma^{tot}_{W^+W^-} = 53.4 \pm 2.1(\mathrm{stat}) \pm 4.5(\mathrm{syst}) \pm 2.1(\mathrm{lumi})$ pb	45.1 ± 2.8 pb
ZZ	4l	$\sigma^{\mathrm{tot}}_{ZZ} = 7.2^{+1.1}_{-0.9}\,(\mathrm{stat})\,^{+0.4}_{-0.3}\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})$ pb	$6.5^{+0.3}_{-0.2}$ pb
ZZ	$ll\nu\nu$	$\sigma^{\mathrm{tot}}_{ZZ} = 5.4^{+1.3}_{-1.2}(\mathrm{stat.})^{+1.4}_{-1.0}(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.})$ pb	$6.5^{+0.3}_{-0.2}$ pb



ATLAS-CONF-2012-025, 26, and 27

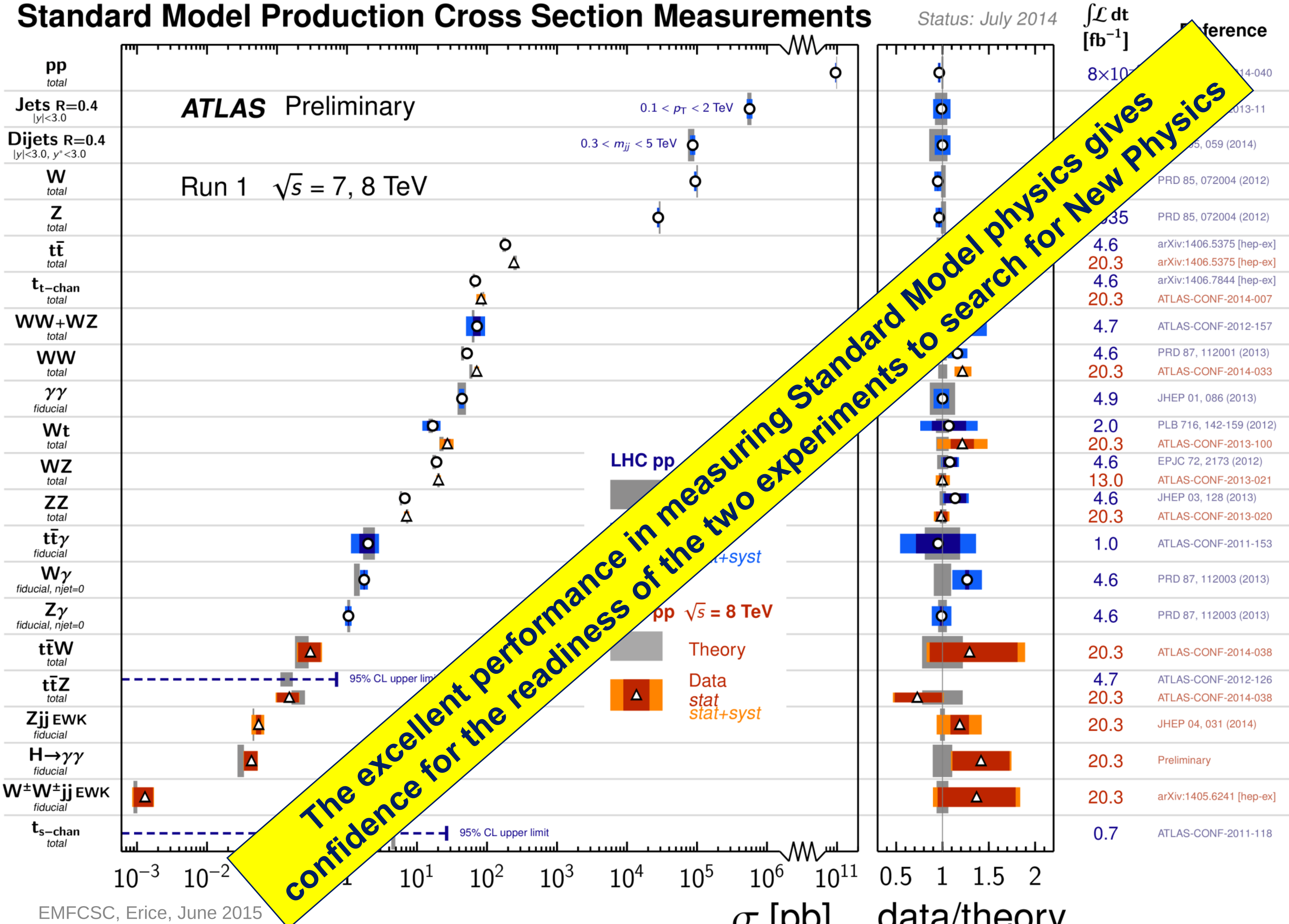






CMS Preliminary
Dec 2014
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
t-ch
tW
s-ch
ttγ
ttZ
ggH
VBF qqH
VH
ttH
All results at: http://cern.ch/go/pNj7
Th. ΔσH in exp. Δσ

Standard Model Production Cross Section Measurements



The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation) ✓
- Detailed simulations of realistic detector “as built and as installed” (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, $Z \rightarrow ll$, …) ✓
- “Rediscover” Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators) ✓
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

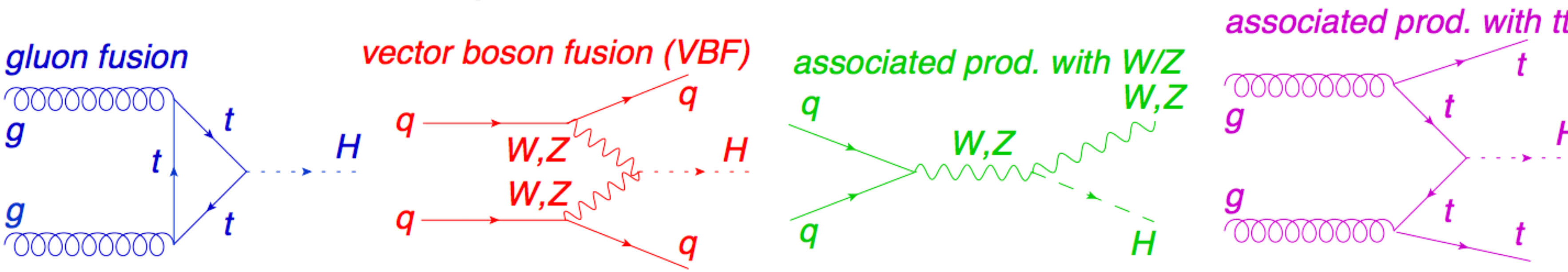
↓

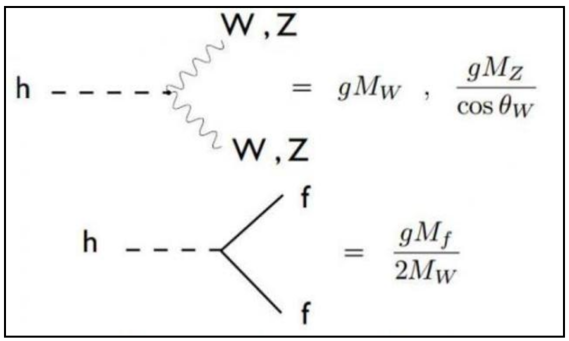
Prepare the road to discoveries …

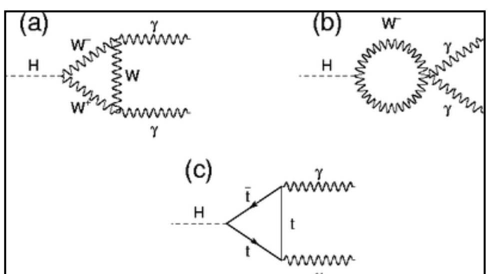

HIGGS BOSON

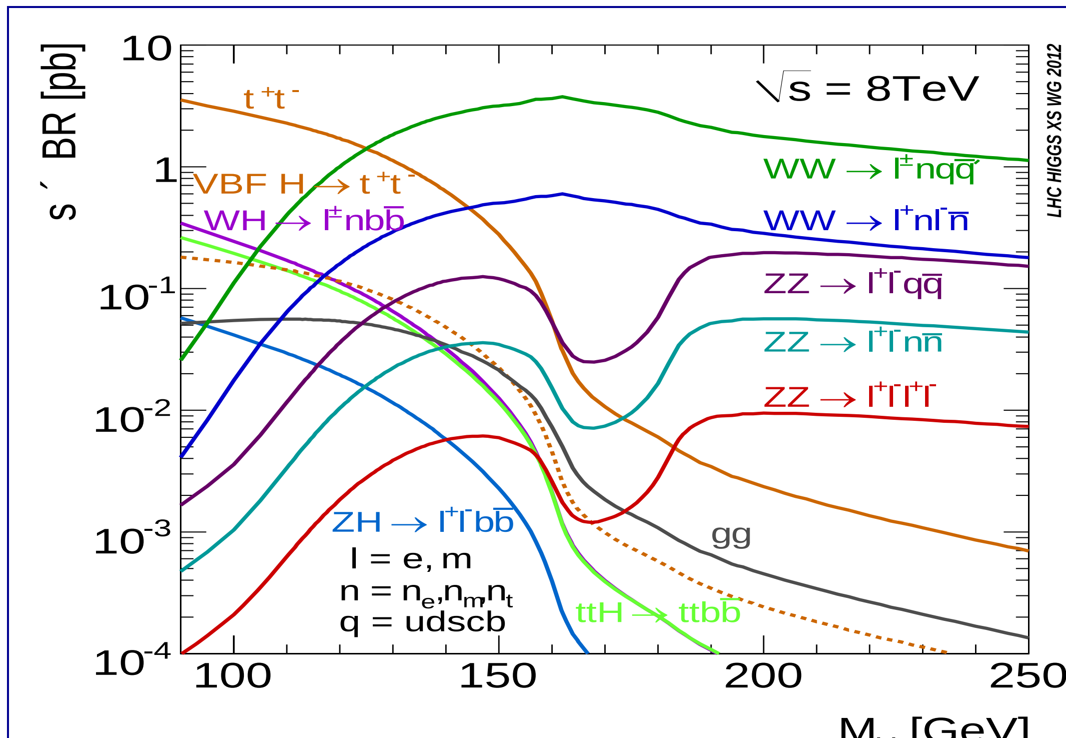
Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 8 TeV

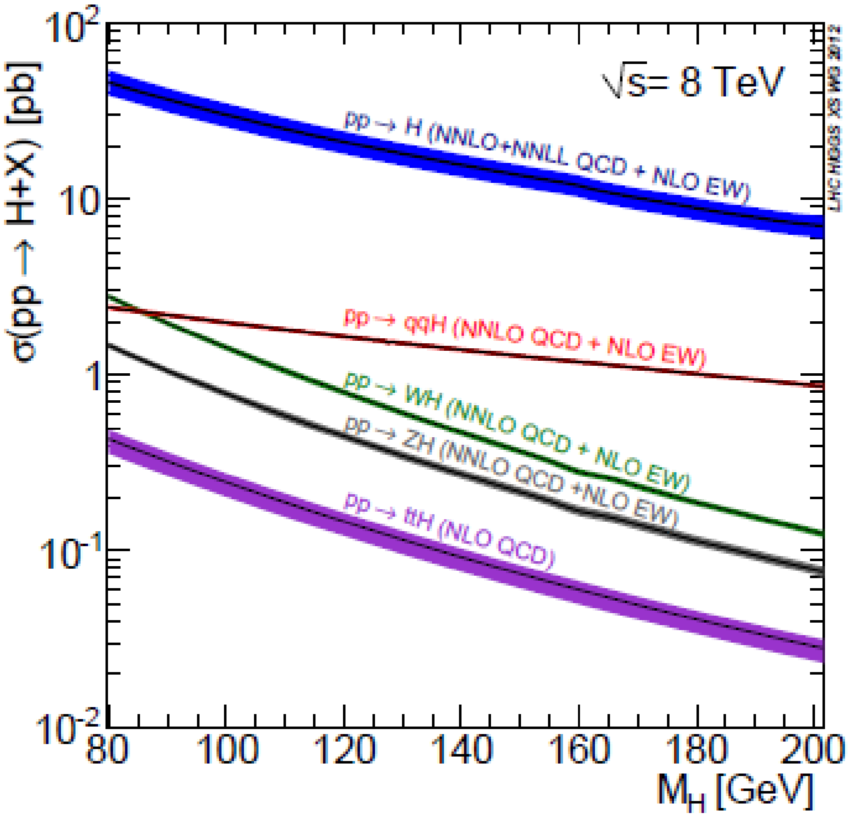


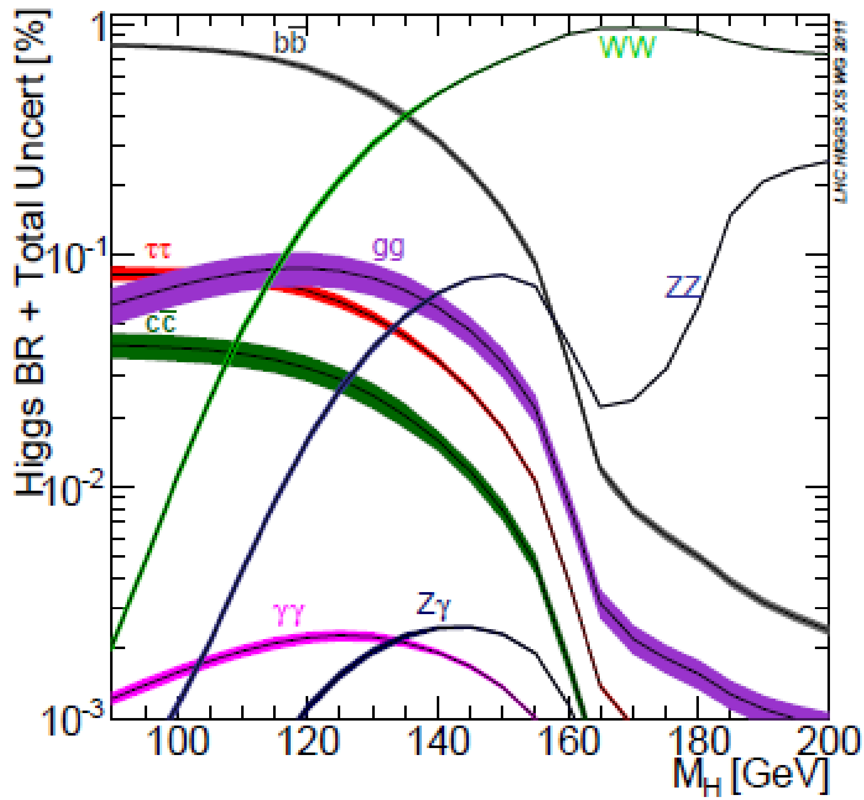






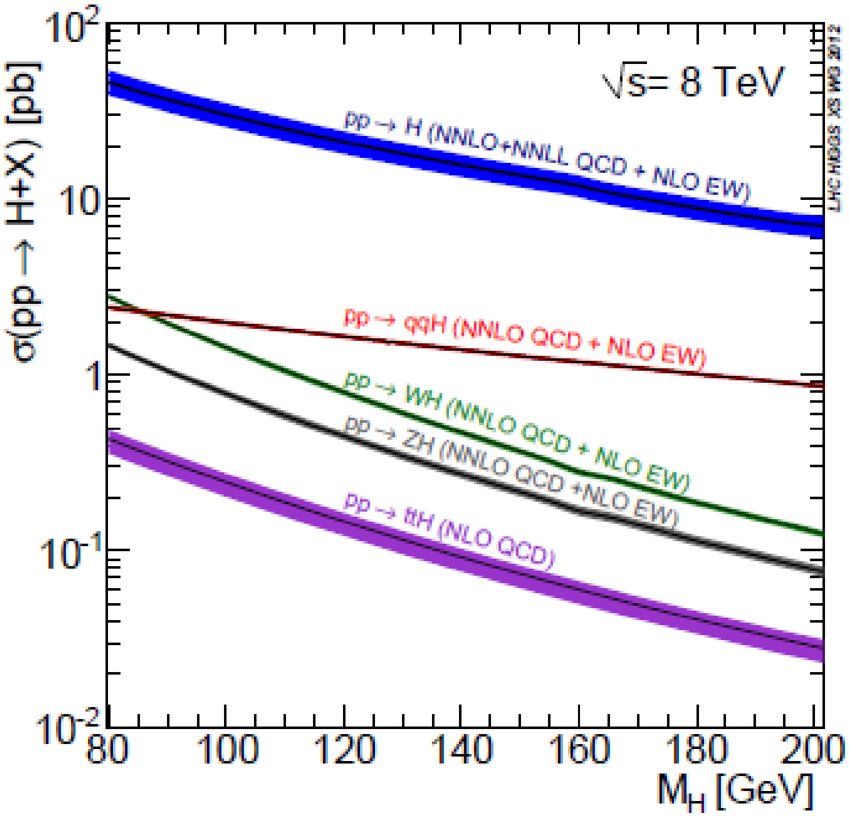
Higgs production cross-sections at 8 TeV, and branching fractions



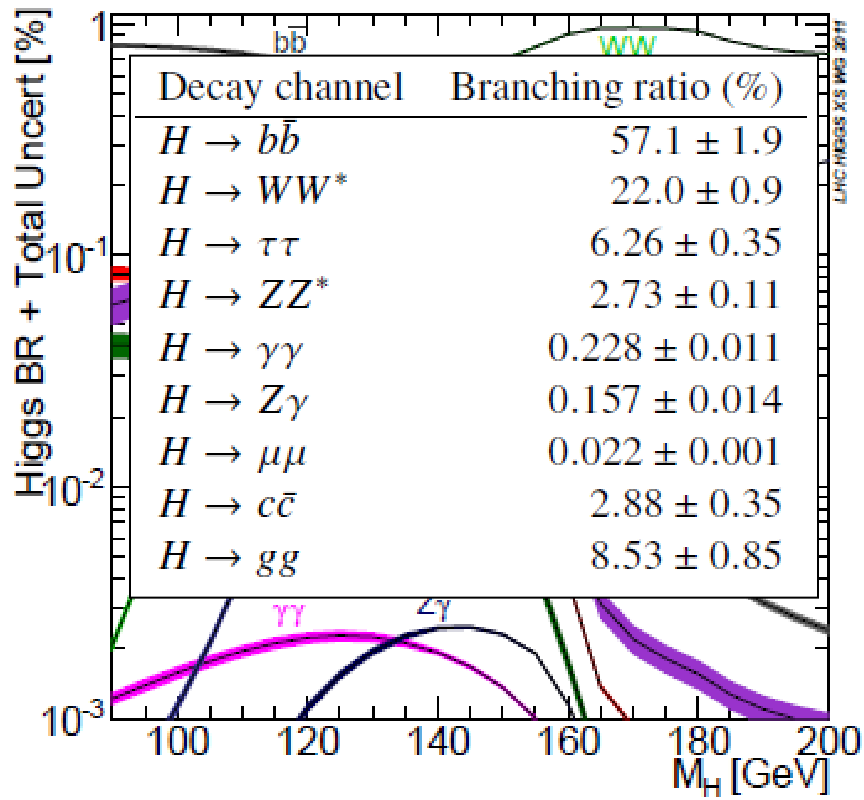


LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084
(the theoretical uncertainties are indicated by the width of the curves)

Higgs production cross-sections at 8 TeV, and branching fractions



@ 125.4 GeV

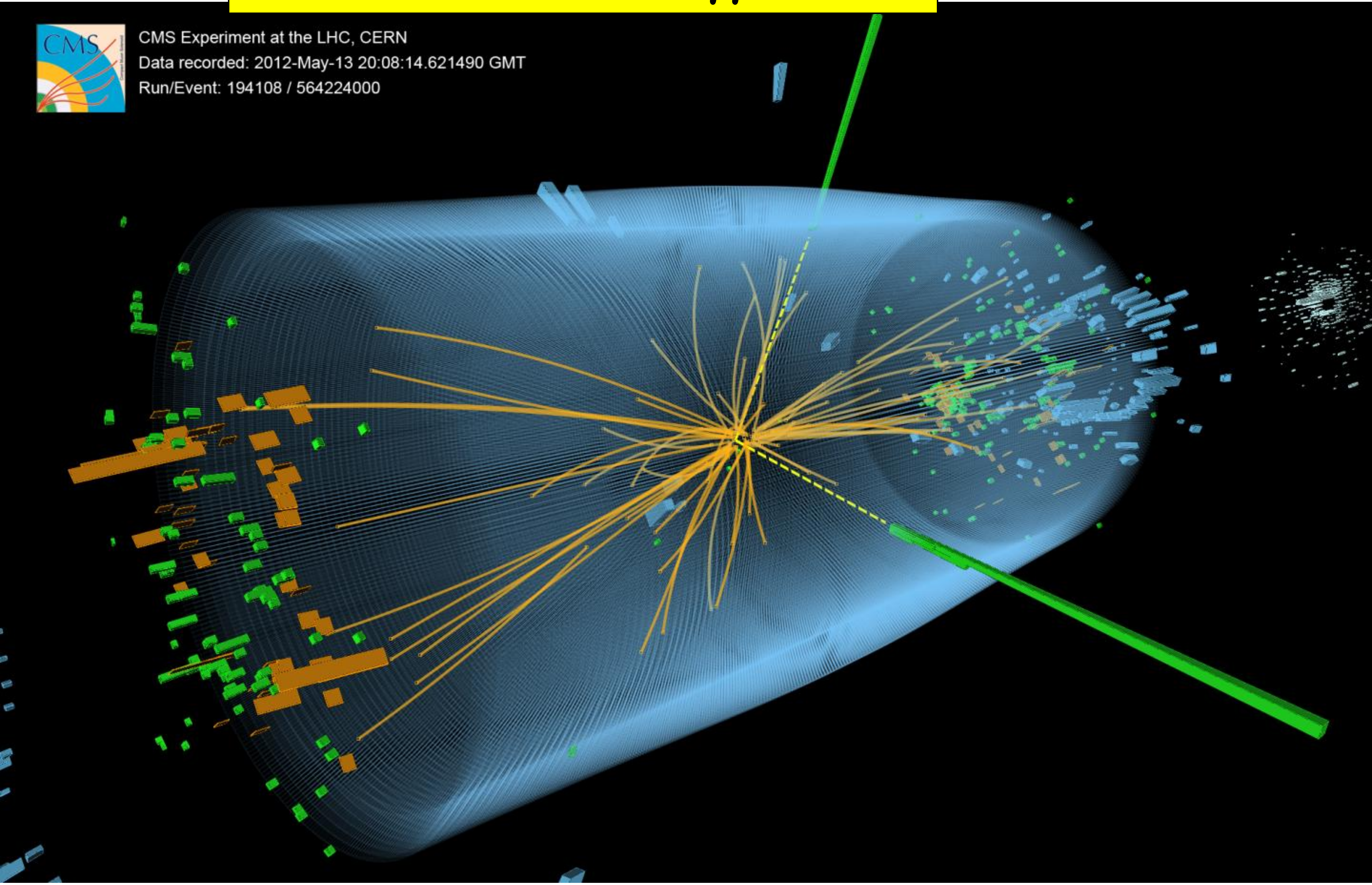


Decay channel	Branching ratio (%)
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to \tau\tau$	6.26 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001
$H \to c\bar{c}$	2.88 ± 0.35
$H \to gg$	8.53 ± 0.85

LHC Higgs cross-section working group, arXiv: 1101.0593 and 1201.3084
(the theoretical uncertainties are indicated by the width of the curves)

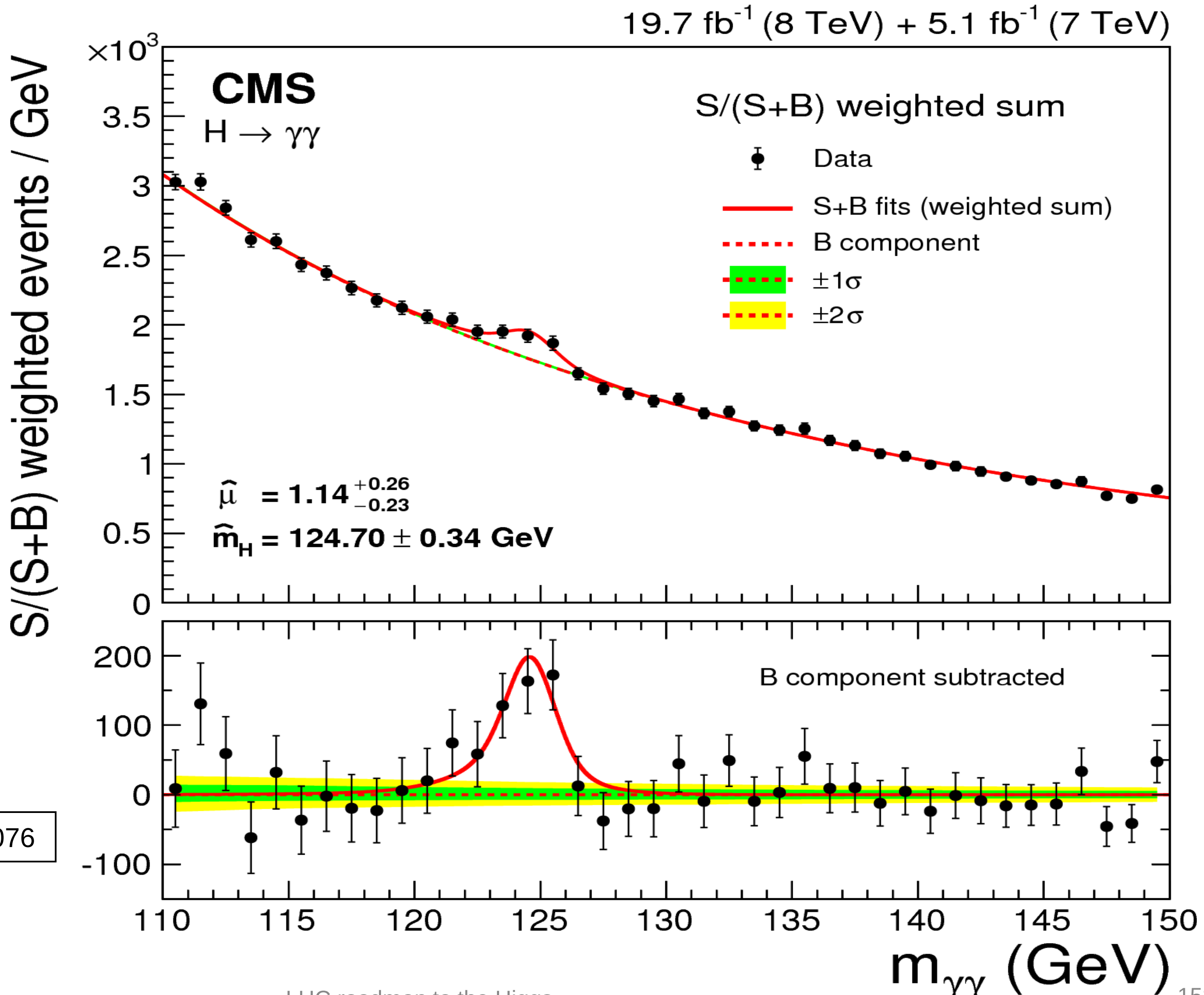
Very happy faces after the announcement of the discovery on 4th July 2012

Candidate for a H → γγ event



H → γγ

- Small cross-section: σ ~ 40 fb
- Expected S/B ~ 0.02
- Simple final state: two high-p_T isolated photons
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)



Eur. Phys. Jour. C74 (2014) 3076

H → γγ

- Small cross-section: σ ~ 40 fb
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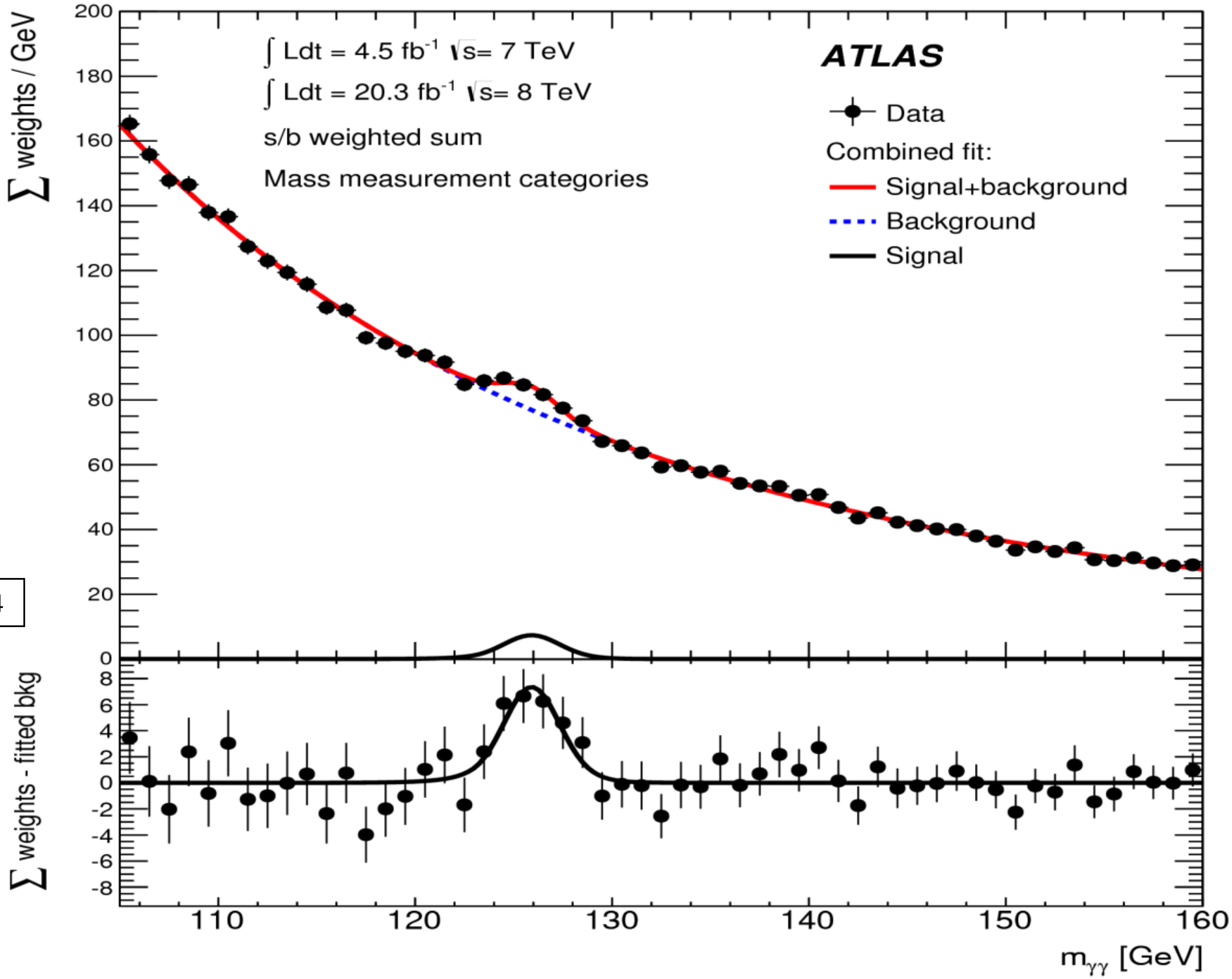
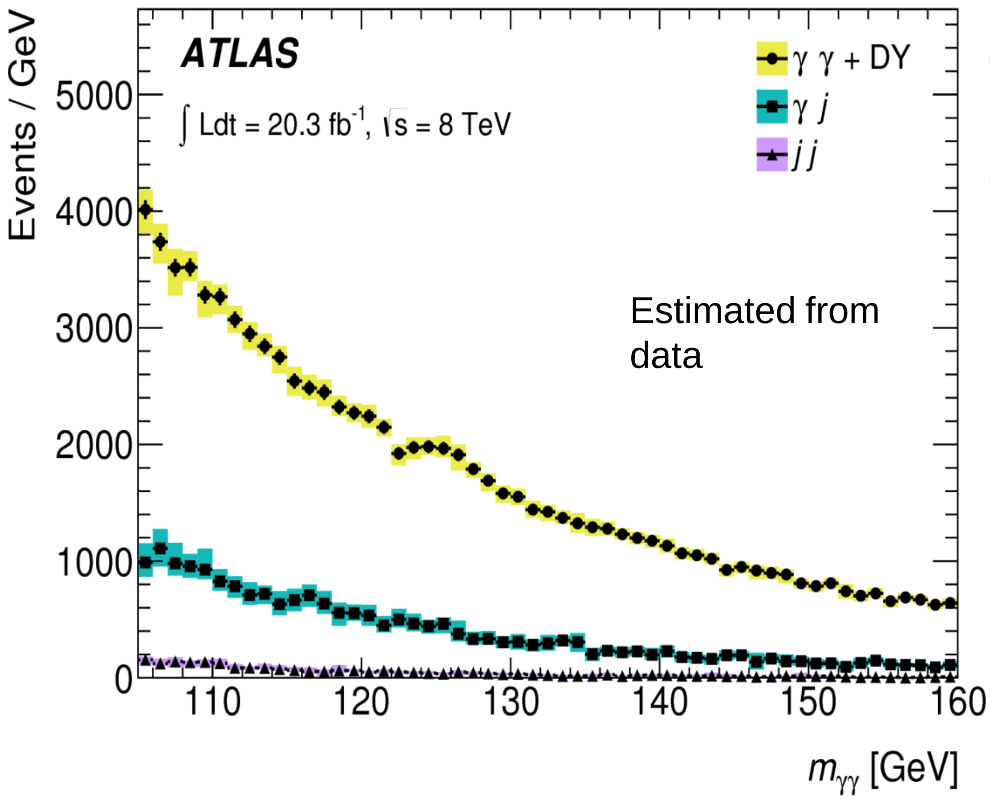
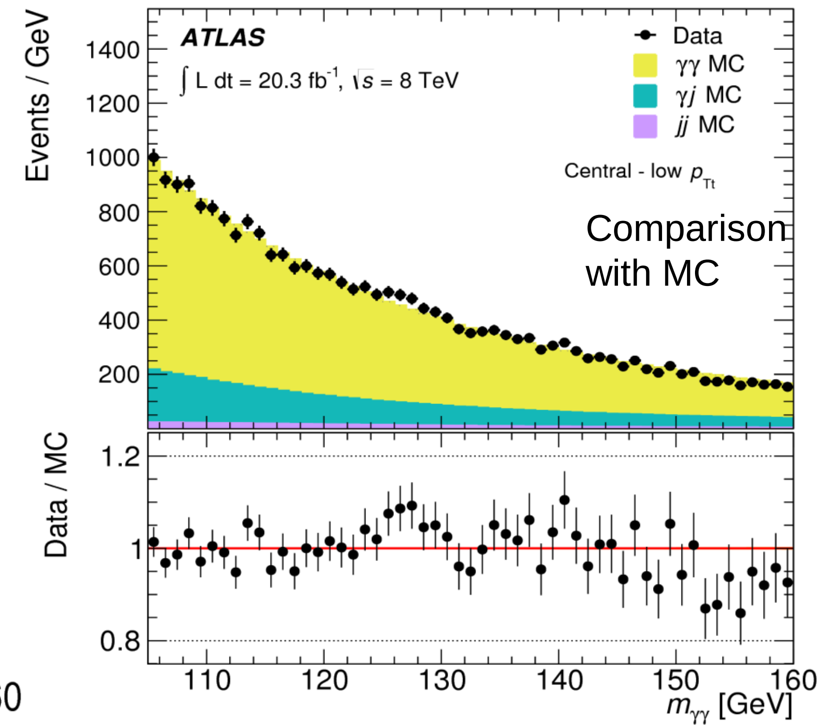
- Simple final state: two high-p_T isolated photons
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)



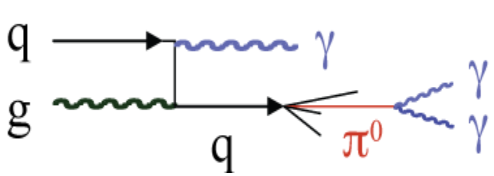
Phys. Rev. D 90 (2014) 052004

Purity of the γγ distribution

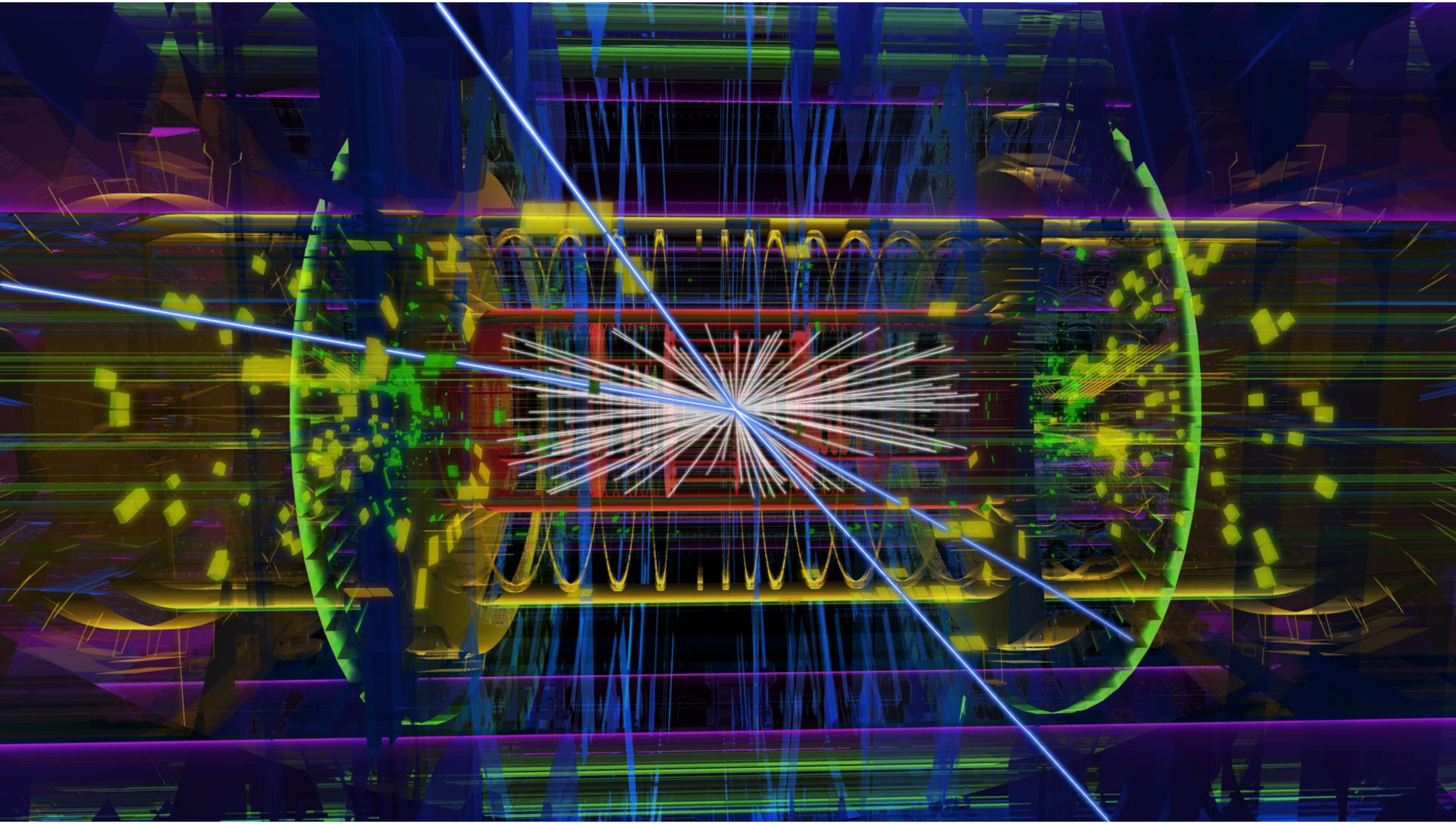




Phys. Rev. D 90 (2014) 112015



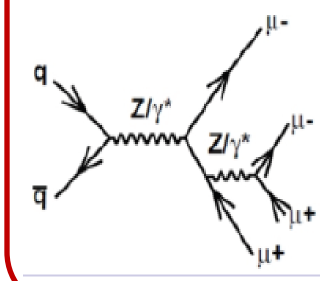
Candidate for a $H \rightarrow ZZ^{*} \rightarrow \mu\mu\ \mu\mu$ event

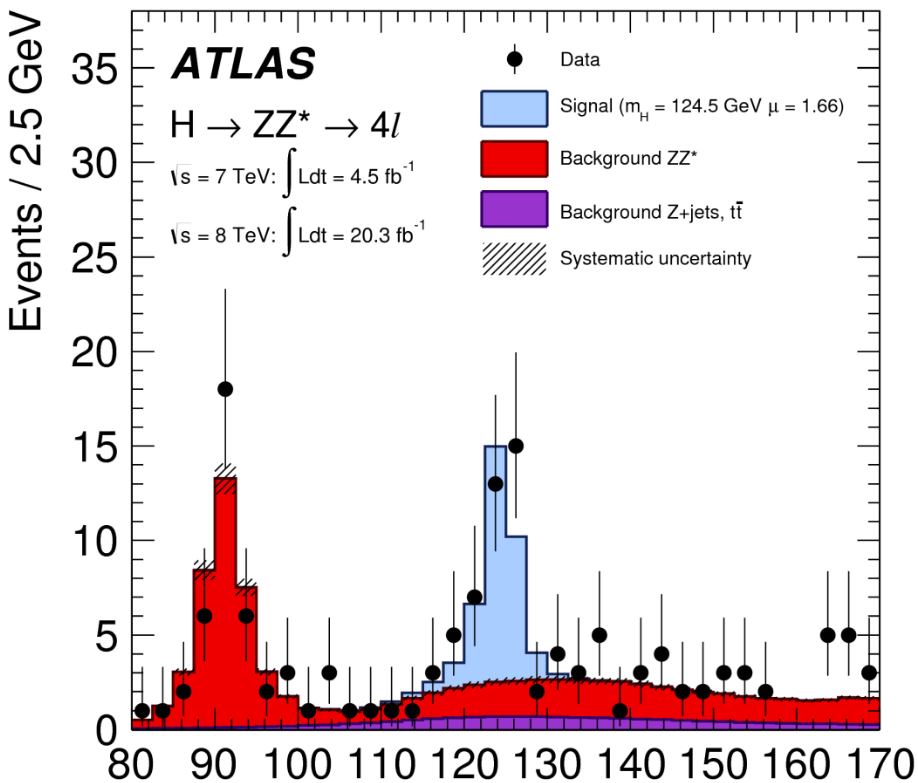


$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

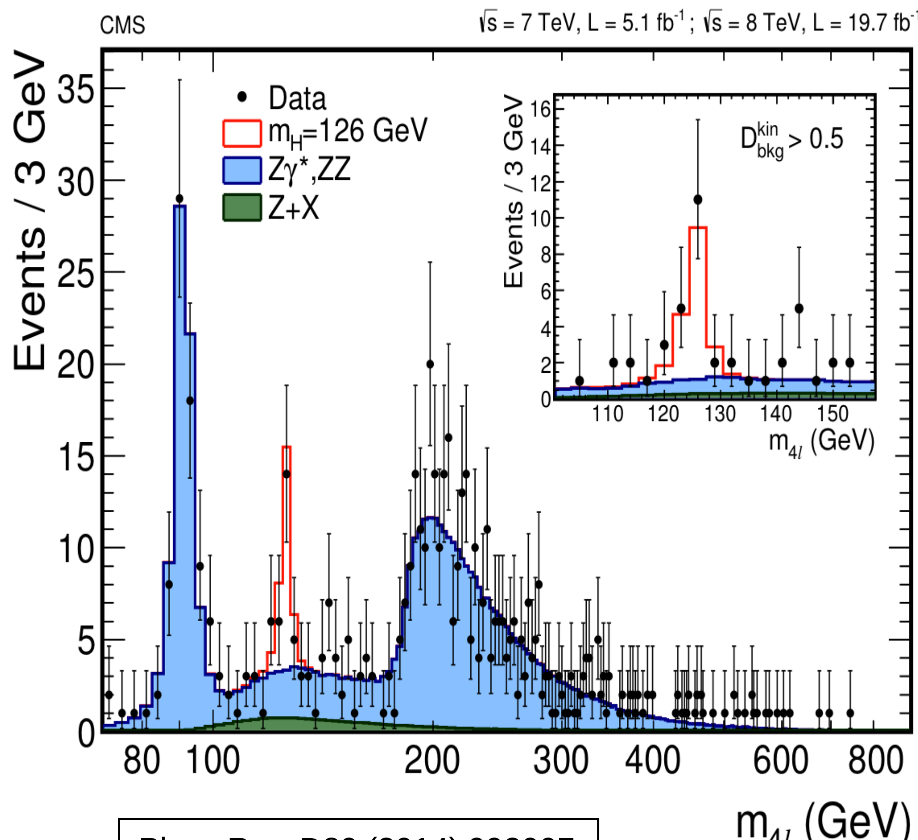
- ❑ **Rare process, small cross section: σ ~ 2-5 fb**
- ❑ **However: pure: S/B ~ 1**
- ❑ **4 leptons:**
- ❑ **Main background: $ZZ^{(*)}$ (irreducible)**
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets

Why a Z peak ?



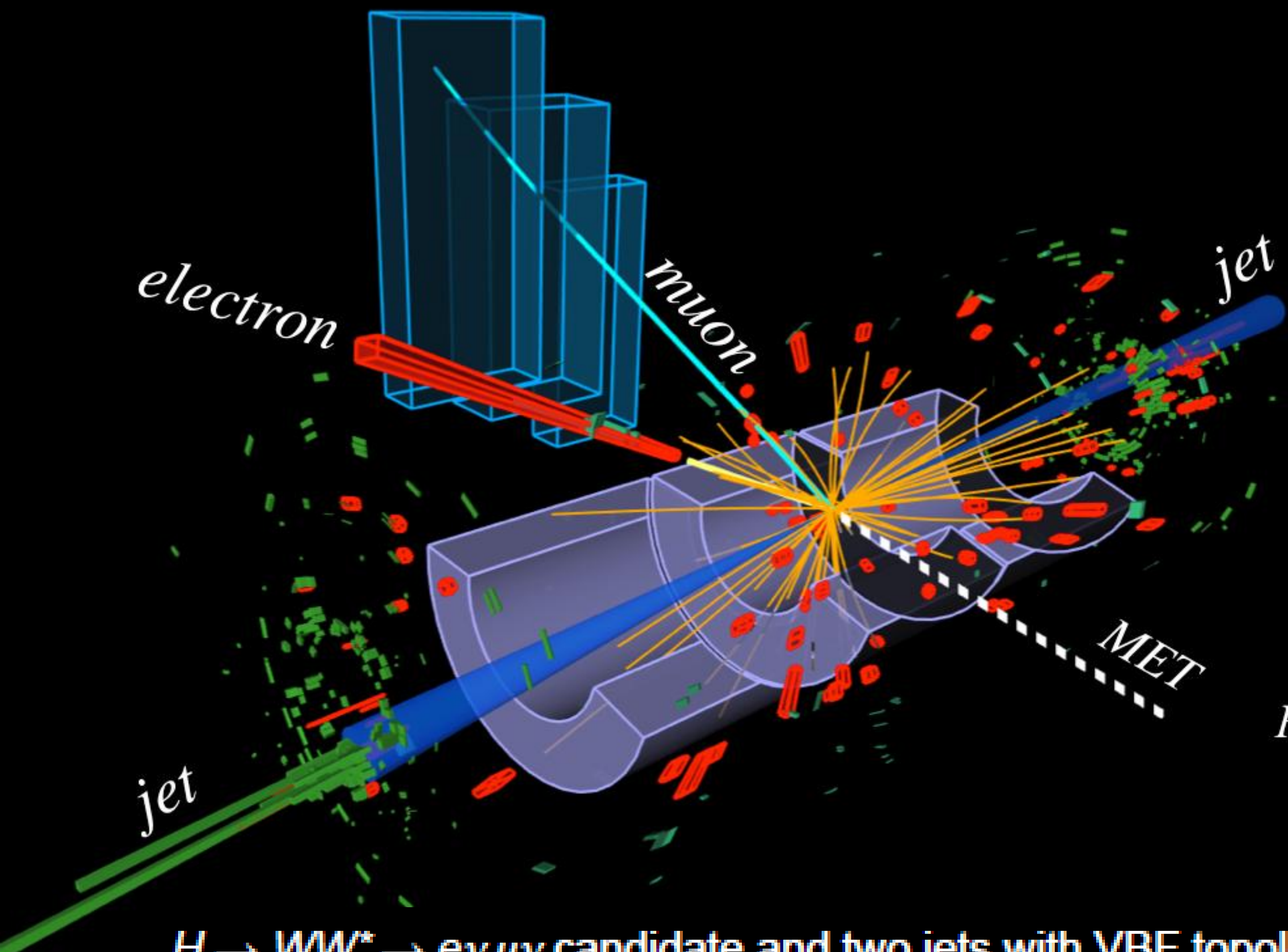


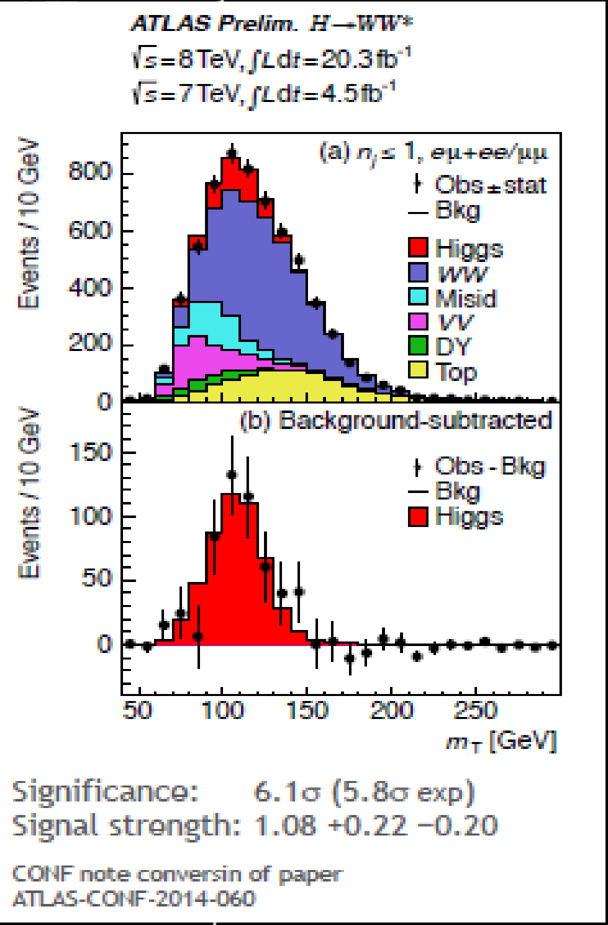
Phys. Rev. D 90 (2014) 052004



Phys. Rev. D89 (2014) 092007

arXiv:1412.2641v![hep-ex] sub. to Phys. Rev. D

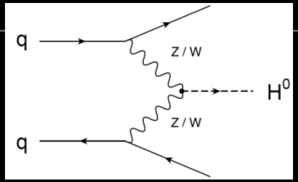




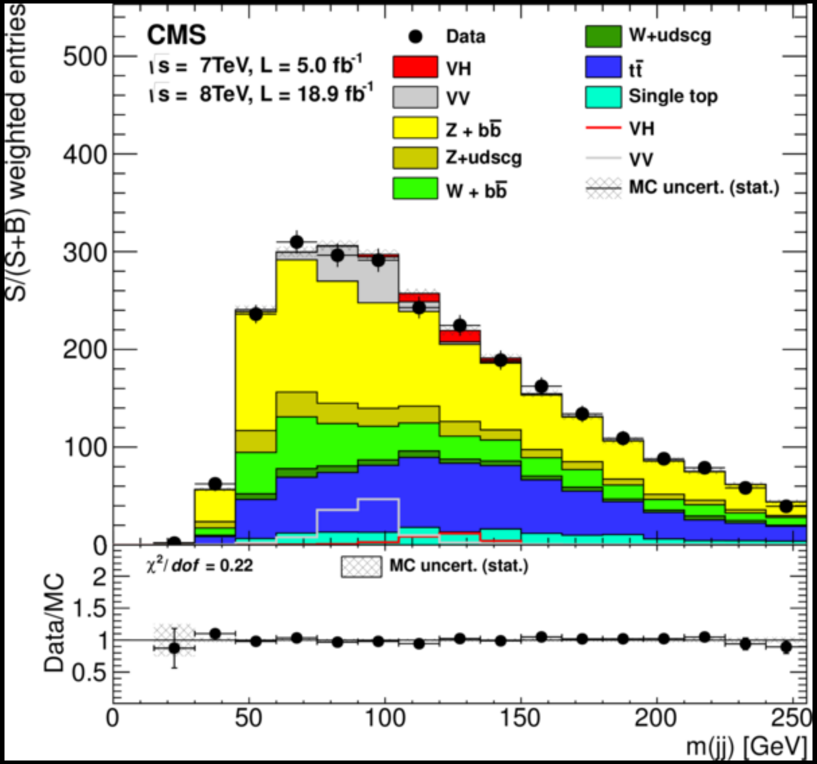
Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

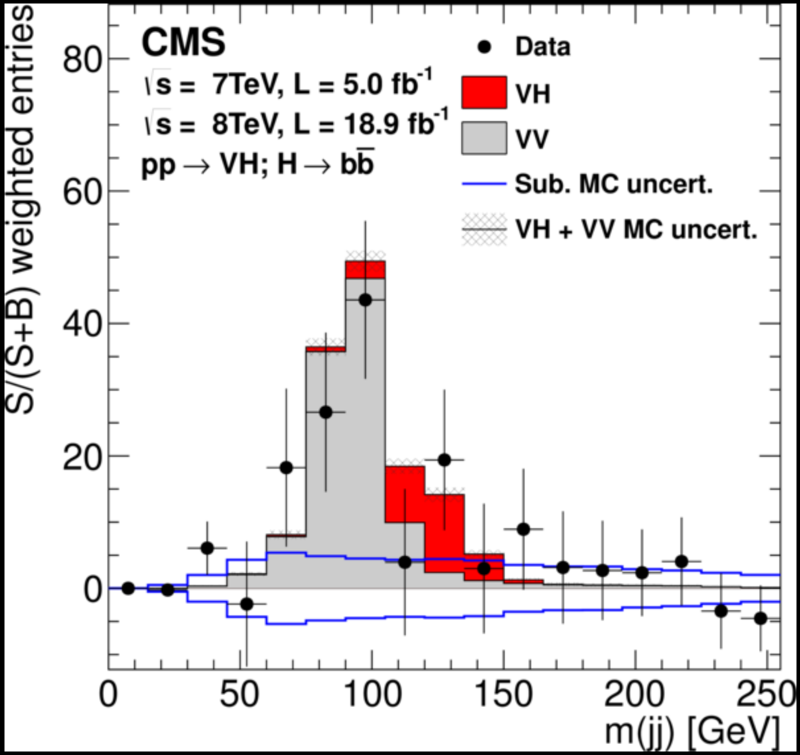
ATLAS EXPERIMENT
http://atlas.ch

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology



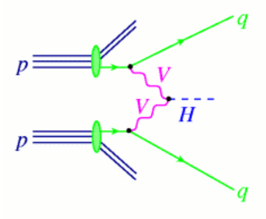
H search in the bb channel, for H produced in association with a W or Z





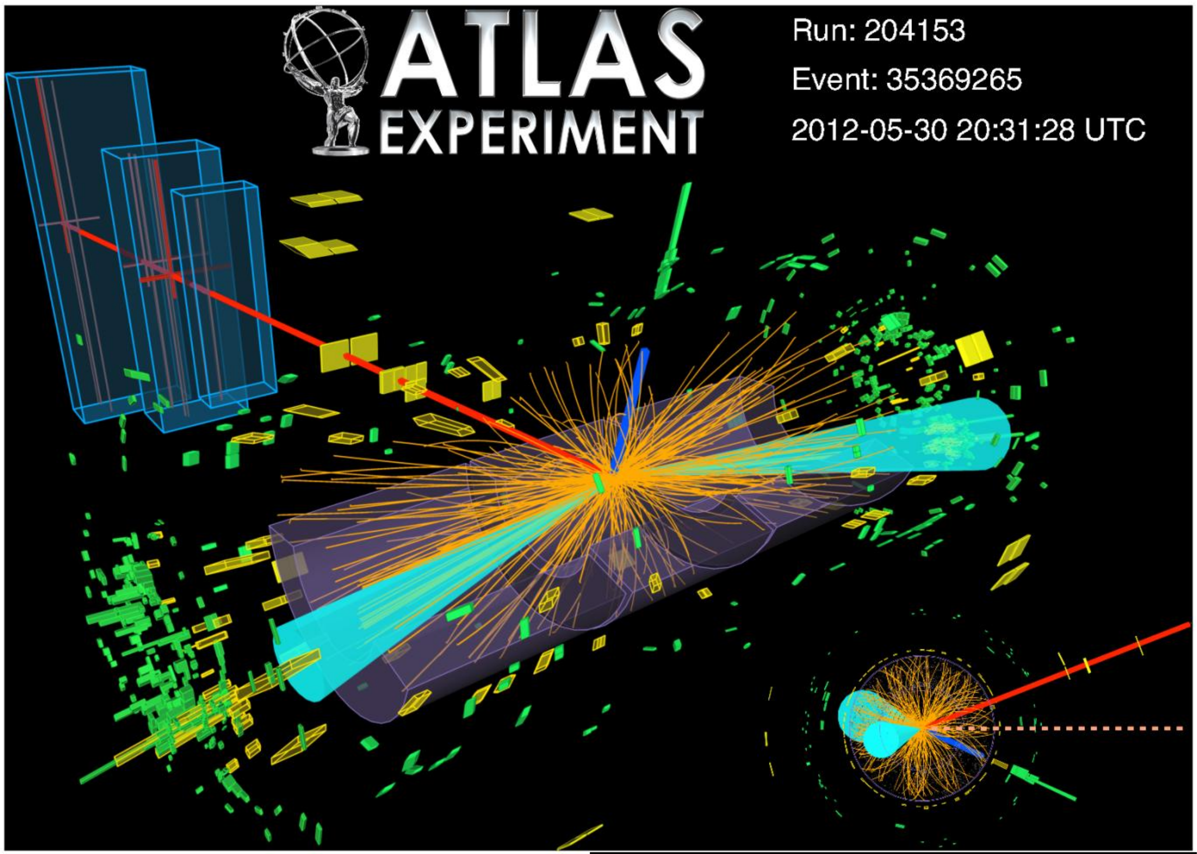
Phys. Rev. D 89, 012003 (2014)

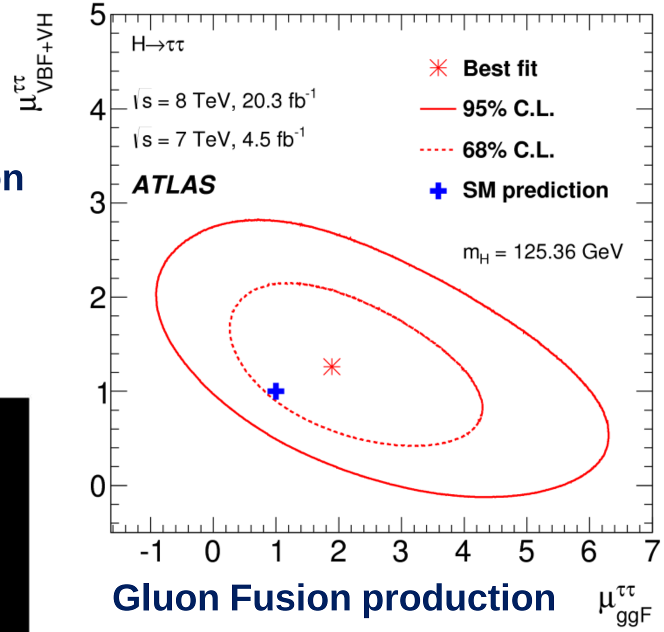
$H \rightarrow \tau\tau \rightarrow \tau_{lep}\tau_{lep}$, or $\tau_{lep}\tau_{had}$, or $\tau_{had}\tau_{had}$



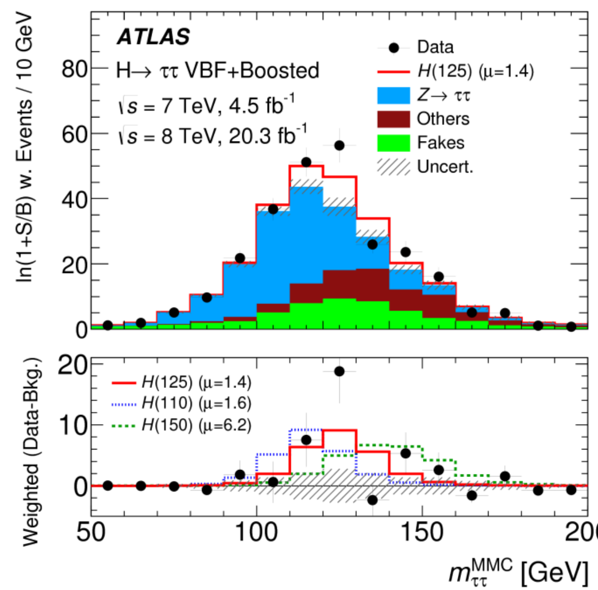
Vector Boson Fusion production

$H \rightarrow \tau_{lep}\ \tau_{lep}$ candidate from the VBF category





Gluon Fusion production



arXiv:1501.04943[hep-ex] sub. to JHEP

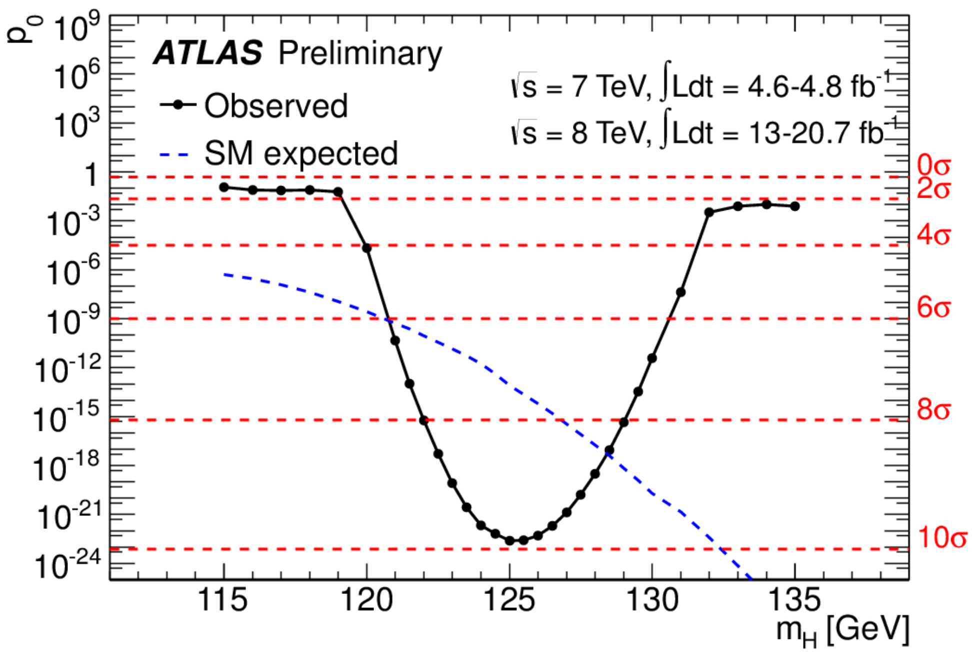
How significant is the signal for the new particle ?

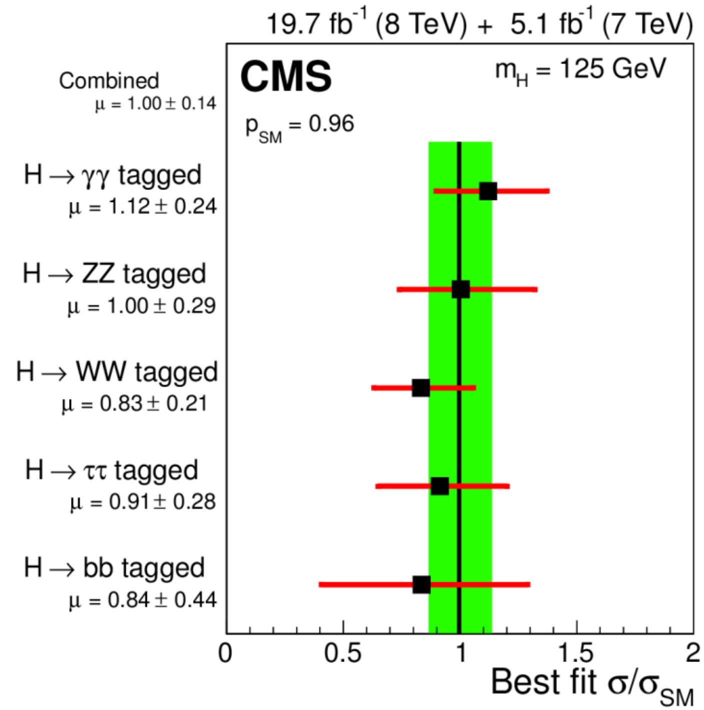
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

Signal strength

$\mu = 0$ background only hypothesis

$\mu = 1$ SM Higgs hypothesis





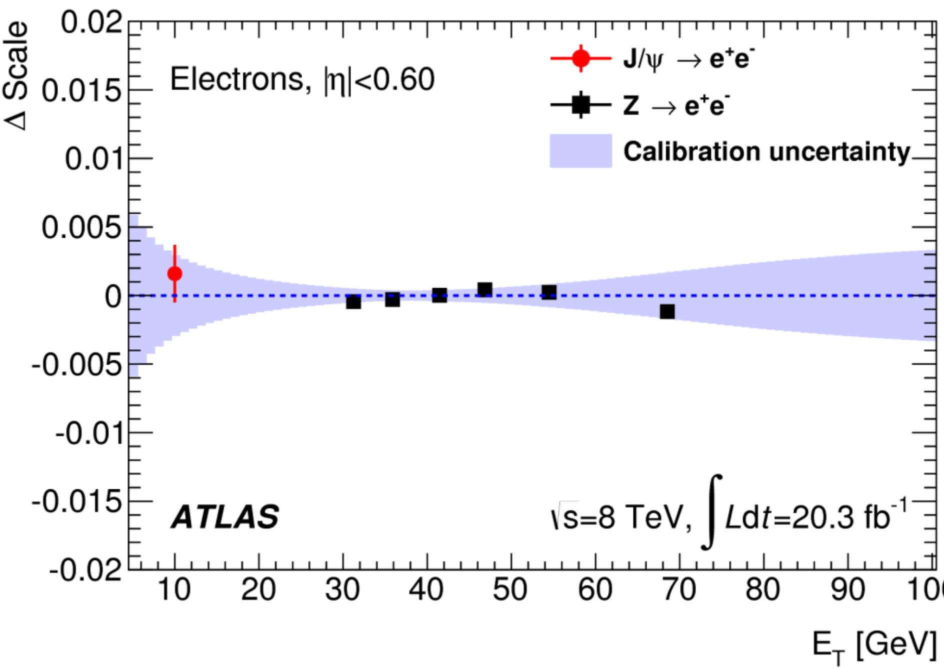
ATLAS-CONF-2013-034, 2014-009

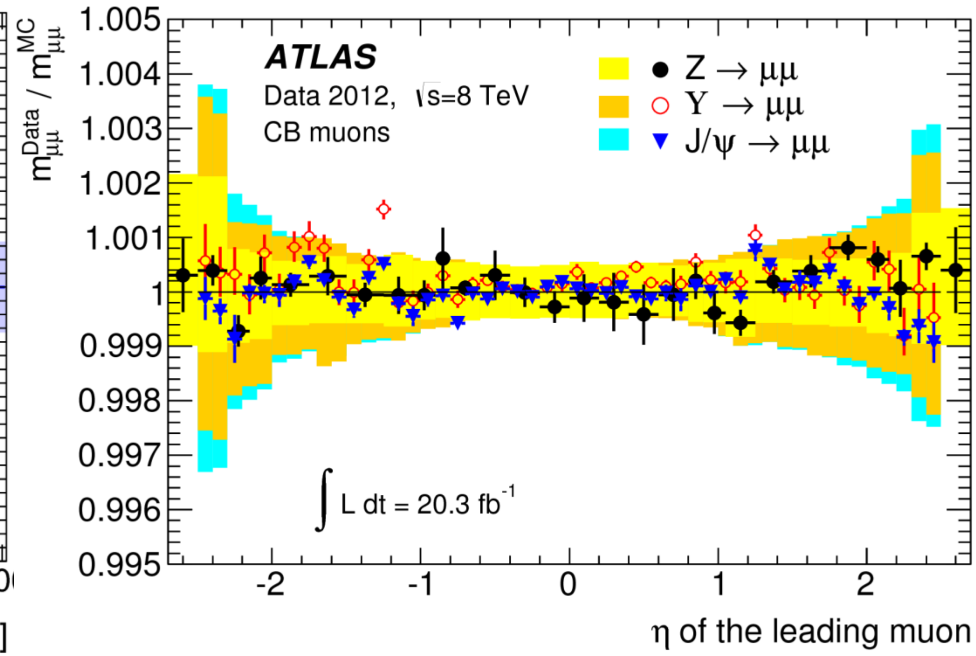
Phys. Rev. D 90 (2014) 052004

CMS arXiv:1412.8662[hep-ex] sub. To Eur. Phys. J. C

$\mu = 1.18 \pm 0.15$ [ATLAS]

$\mu = 1.00 \pm 0.14$ [CMS]



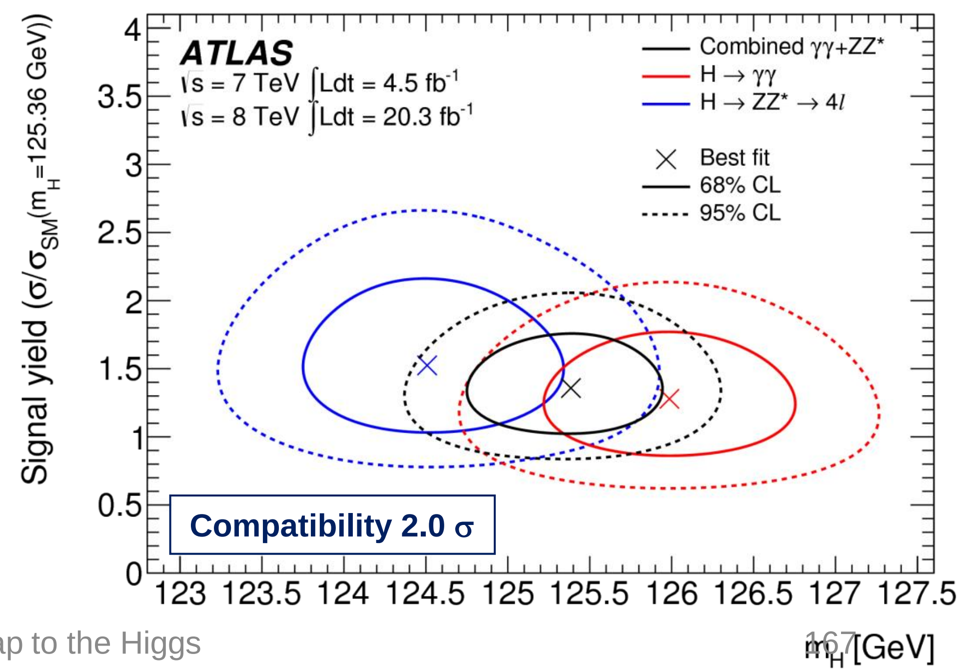


ATLAS Higgs mass measurements [To quote: 'the real work…']

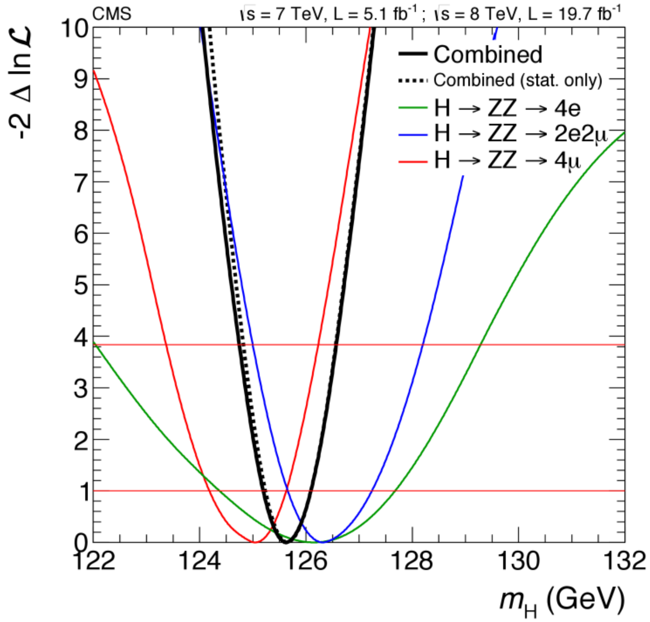
Electron energy and muon momentum calibrations

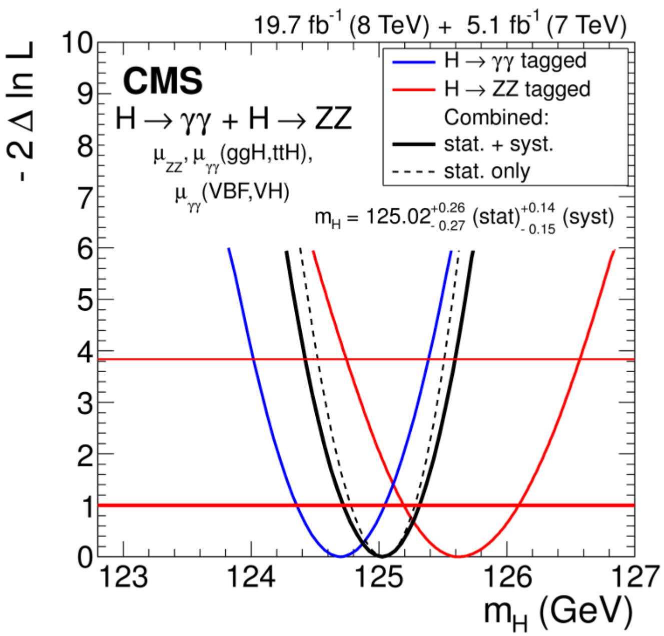
Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

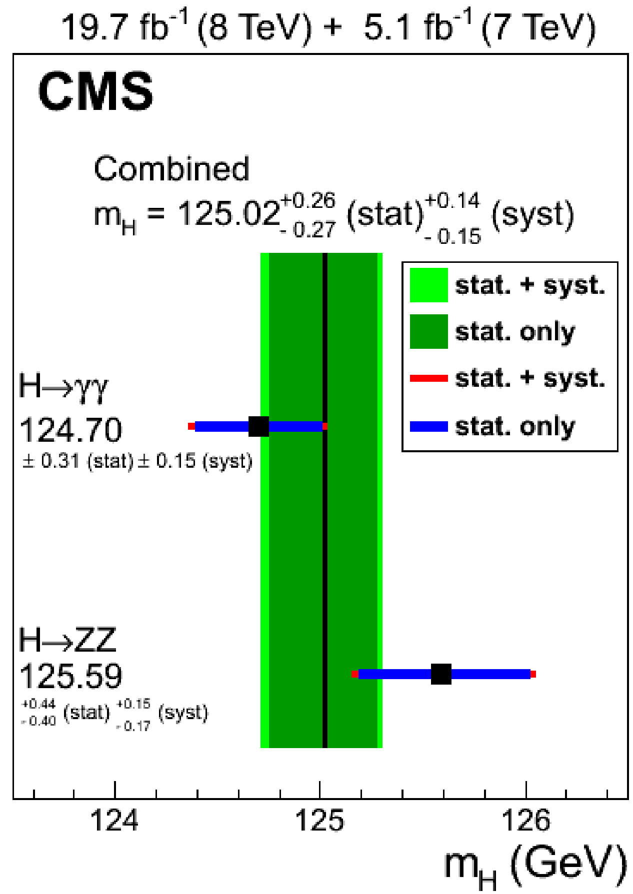
Phys. Rev. D90 (2014) 052004



CMS combined results from the full LHC run 1

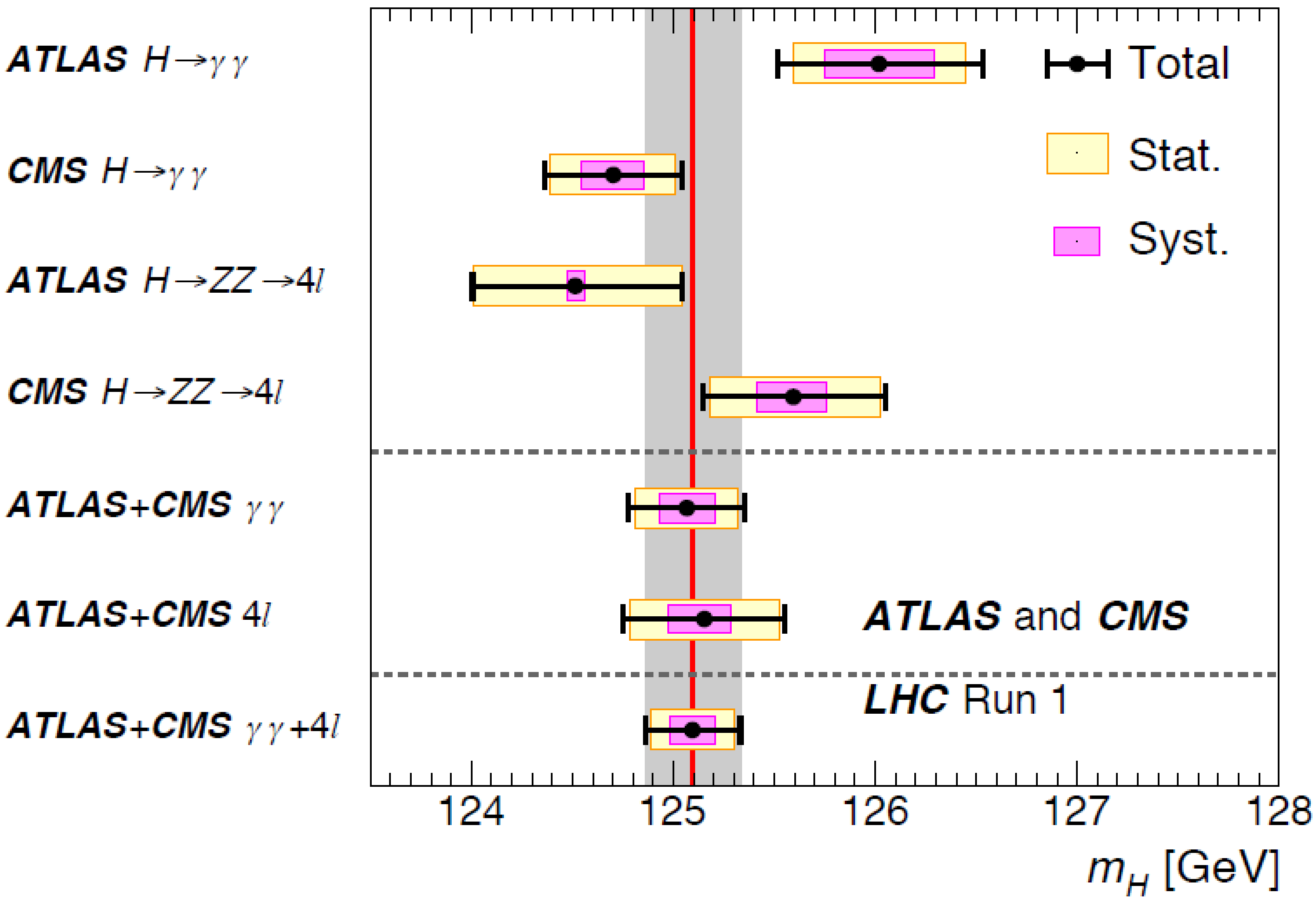






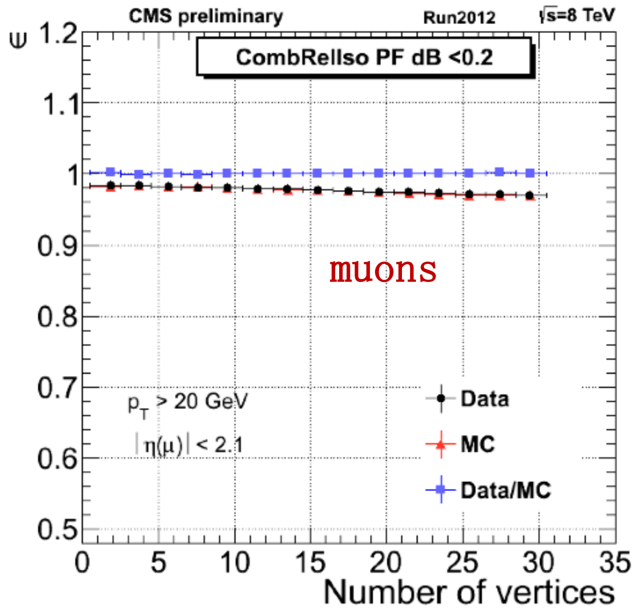
arXiv:1412.8662[hep-ex] sub. To Eur. Phys. J. C

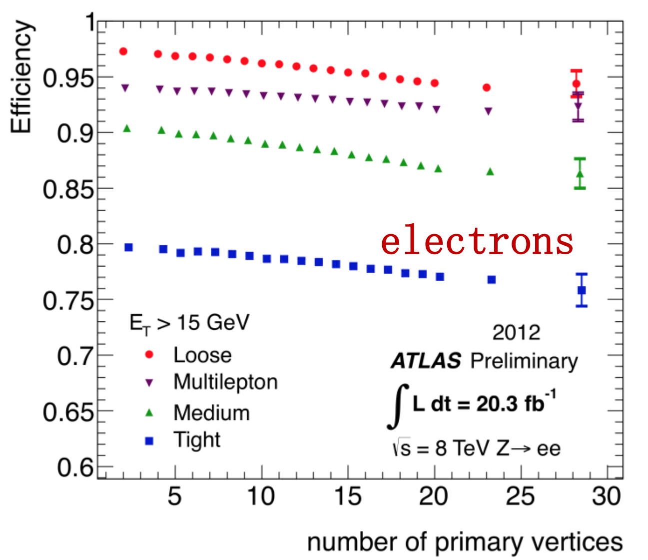
$$m_H = 125.09 \pm 0.24\ (\pm 0.21\ \text{stat} \pm 0.11\ \text{syst})\ \text{GeV}$$

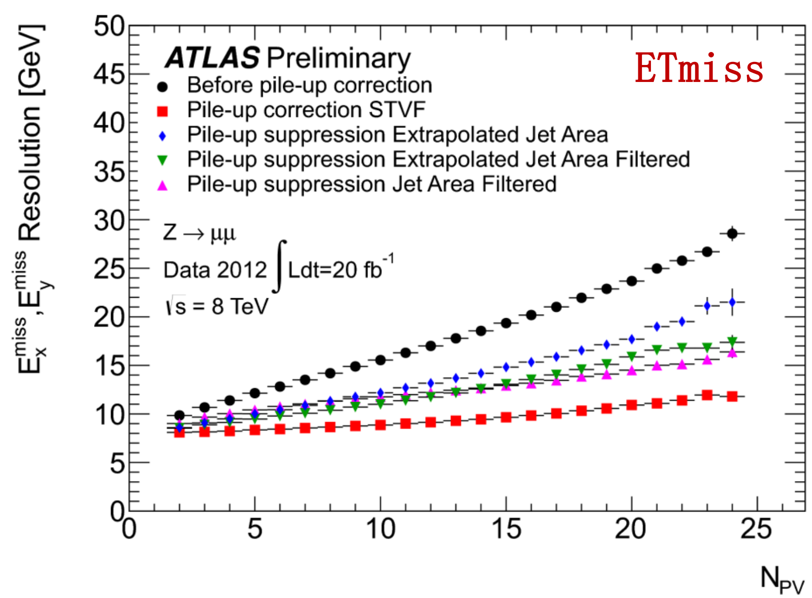


ATLAS+CMS arXiv:1503.07589v1[hep-ex] accepted by Phys. Rev. Lett.

Some illustration that the experiments mastered the pile-up challenges







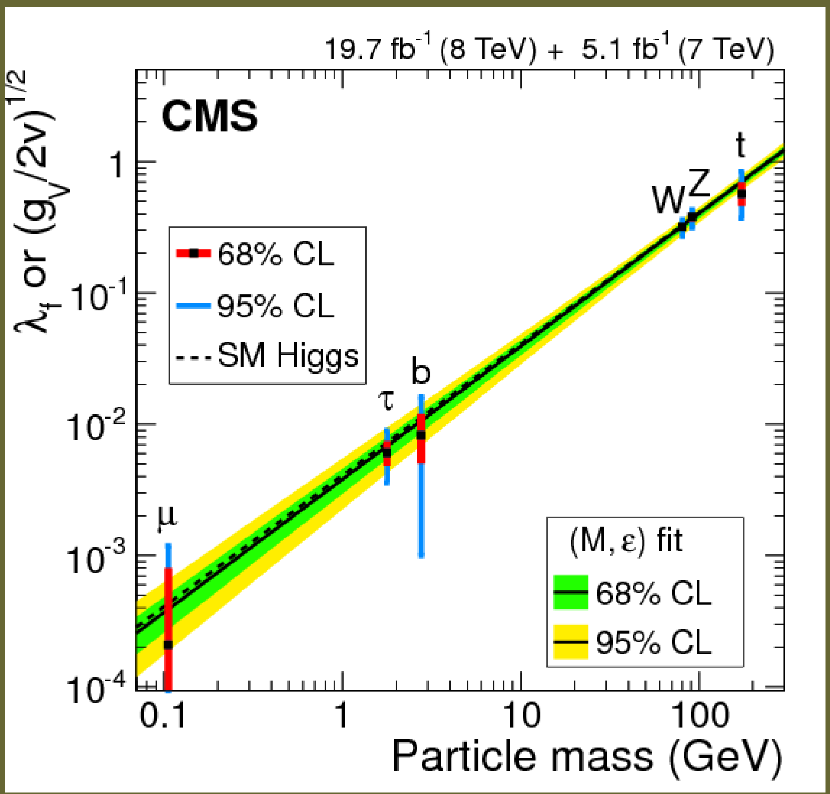
CMS-DP-2012/05

ATLAS-CONF-2014-019

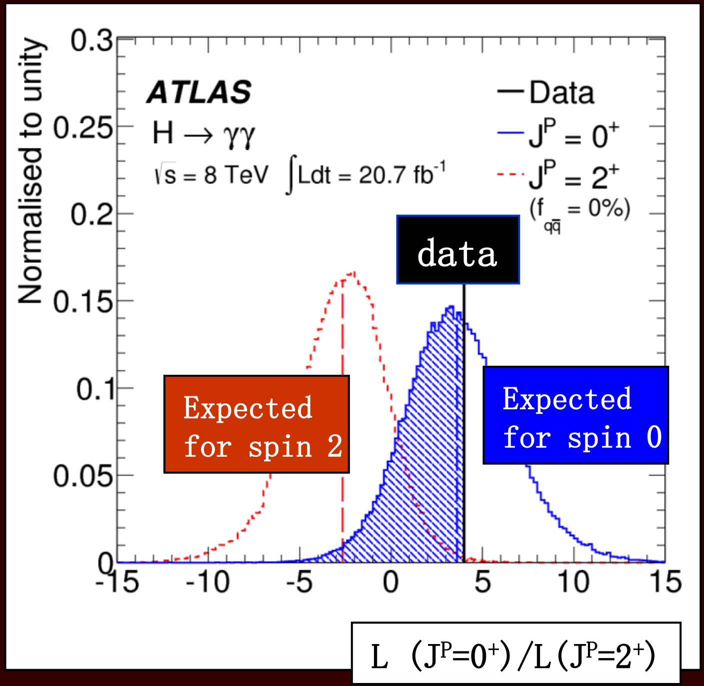
Is the new particle a Higgs boson ?

ATLAS and CMS have verified the two main "fingerprints" for a Higgs …

1) To accomplish its job (providing mass) it interacts with other particles (in particular W, Z) with strength proportional to their masses



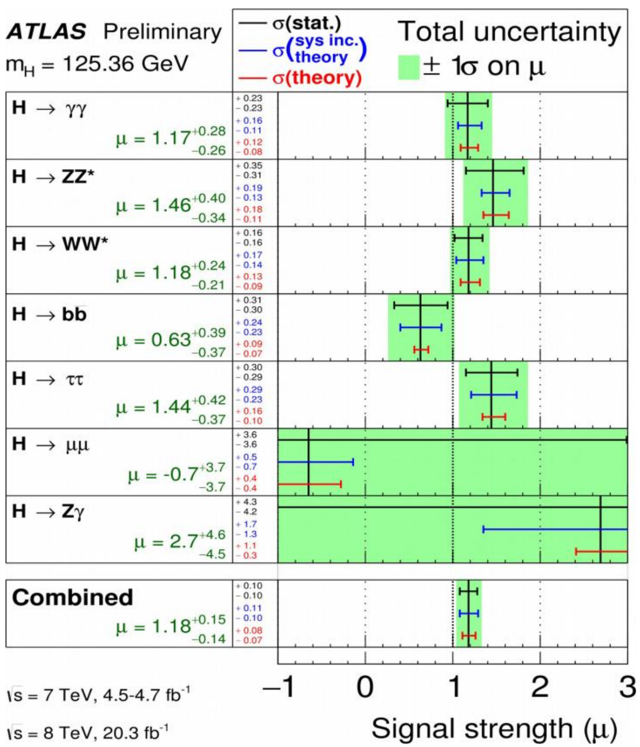
2) It has spin zero (scalar)

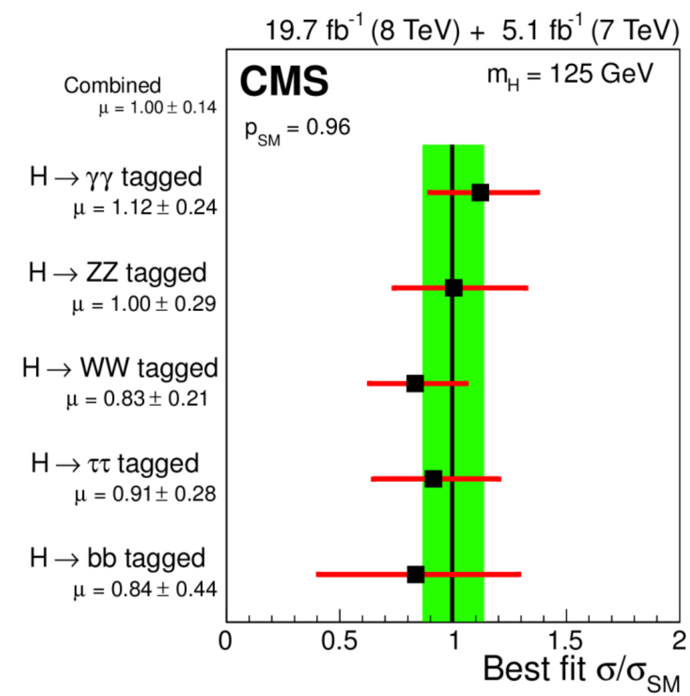


Hypothesis	Rejection (C.L.)
0^-	97.8%
1^+	99.97%
1^-	99.7%
2^+	99.9%

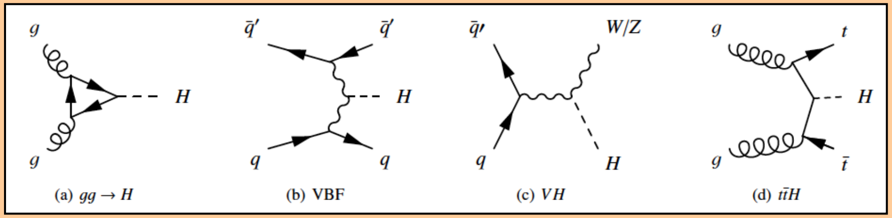
Complementary technologies providing comparable performances in term of significance of the signals !

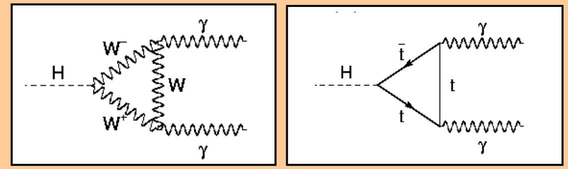
Experiment	ATLAS		CMS	
Decay mode/combination	Expected (σ)	Observed (σ)	Expected (σ)	Observed (σ)
γγ	4.6	5.2	5.3	5.6
ZZ	6.2	8.1	6.3	6.5
WW	5.8	6.1	5.4	4.7
bb	2.6	1.4	2.6	2.0
ττ	3.4	4.5	3.9	3.8





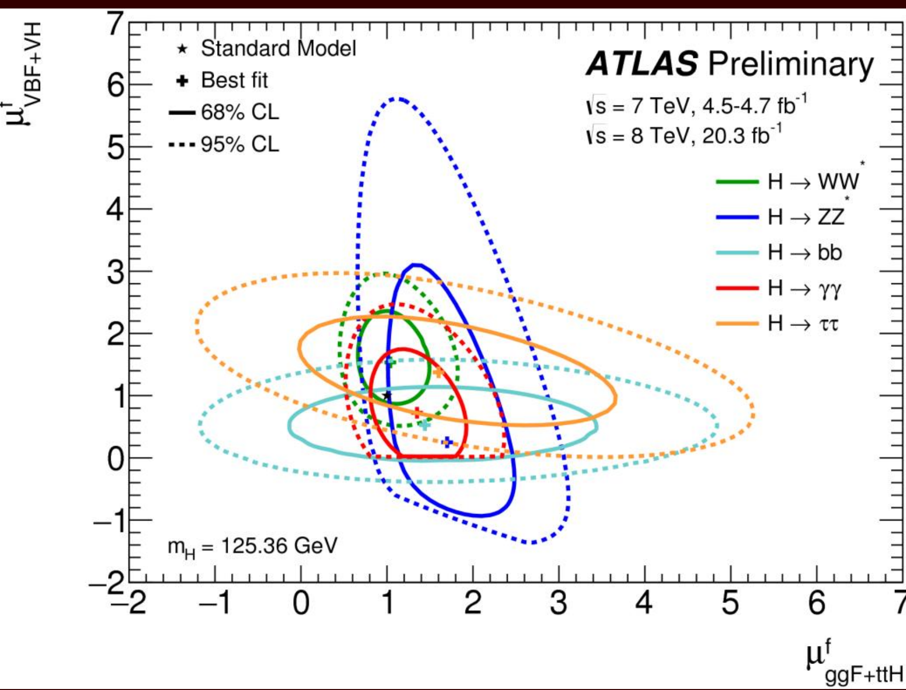
Couplings (examples from many fits to test compatibility with SM)

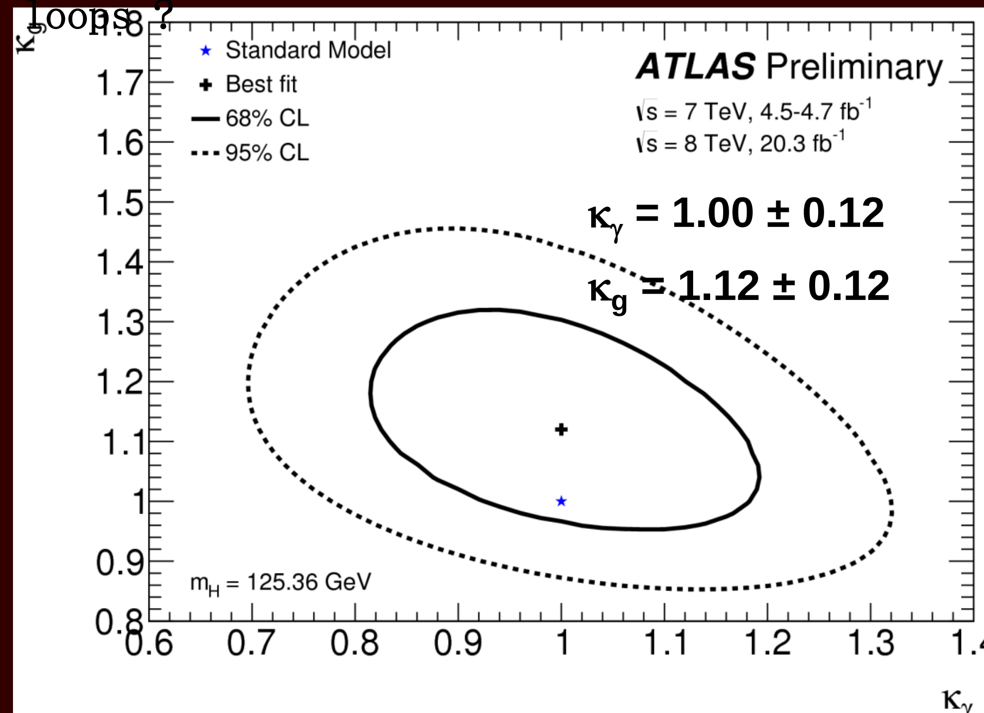




$$k_i^2 = \frac{G_i^{data}}{G_i^{SM}}$$

New particles in the gg → H and H→ γγ loops ?





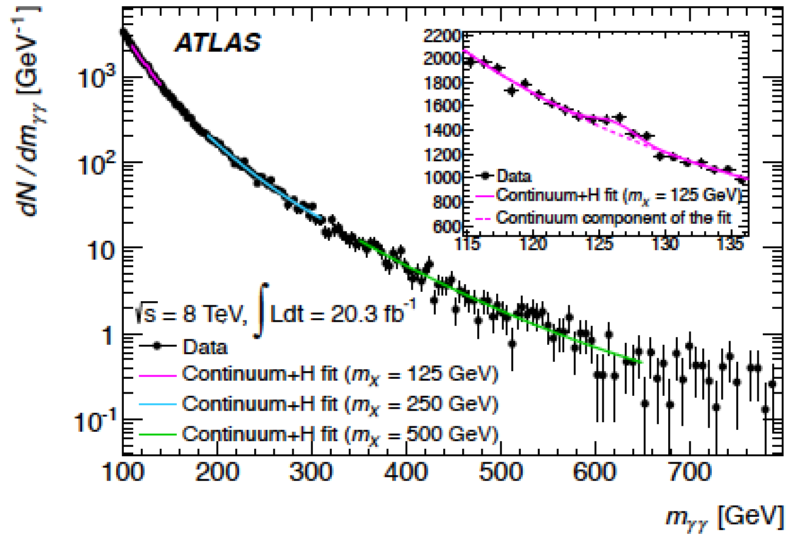
ATLAS-CONF-2015-007

→ New particle couples to other particles with strength proportional to their masses (to accomplish its job → Higgs mechanism) → 1st "fingerprint" of the Higgs boson

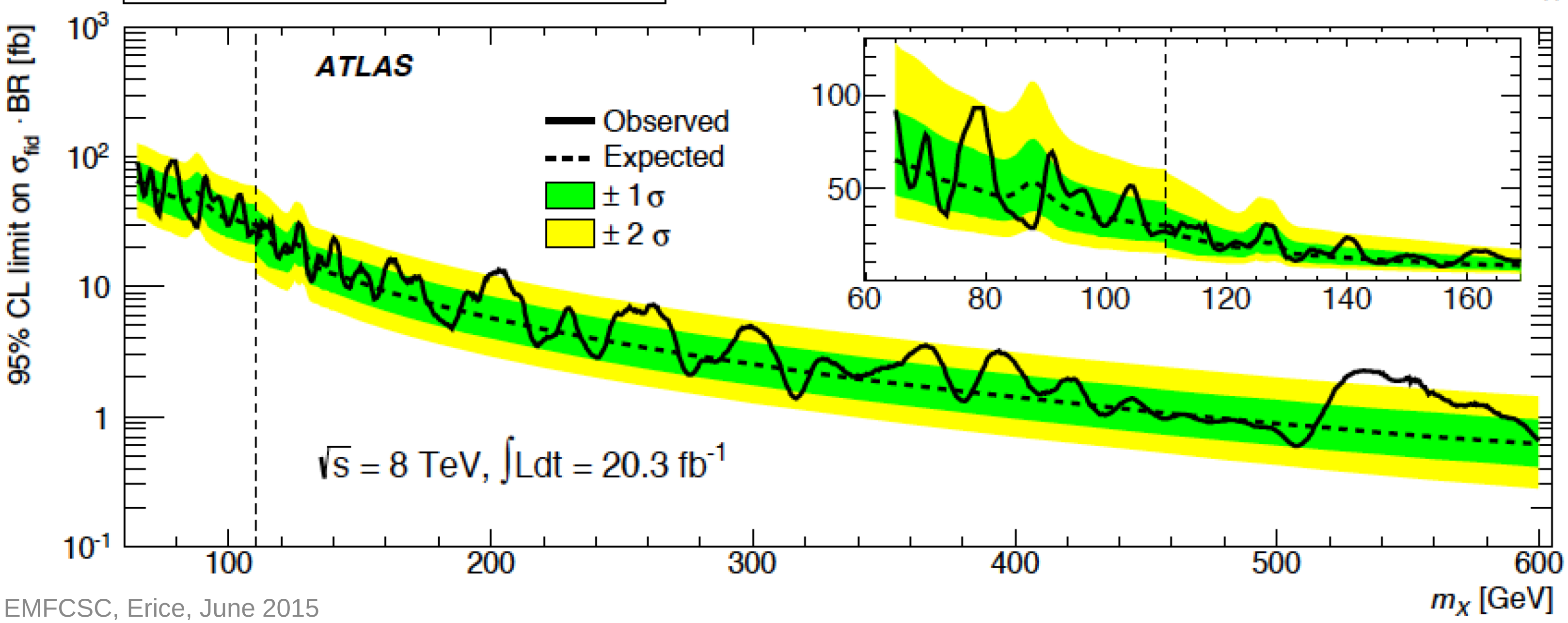
→ No significant New Physics contributions to its couplings (within present uncertaint

Status of high mass search: Higgs → γγ

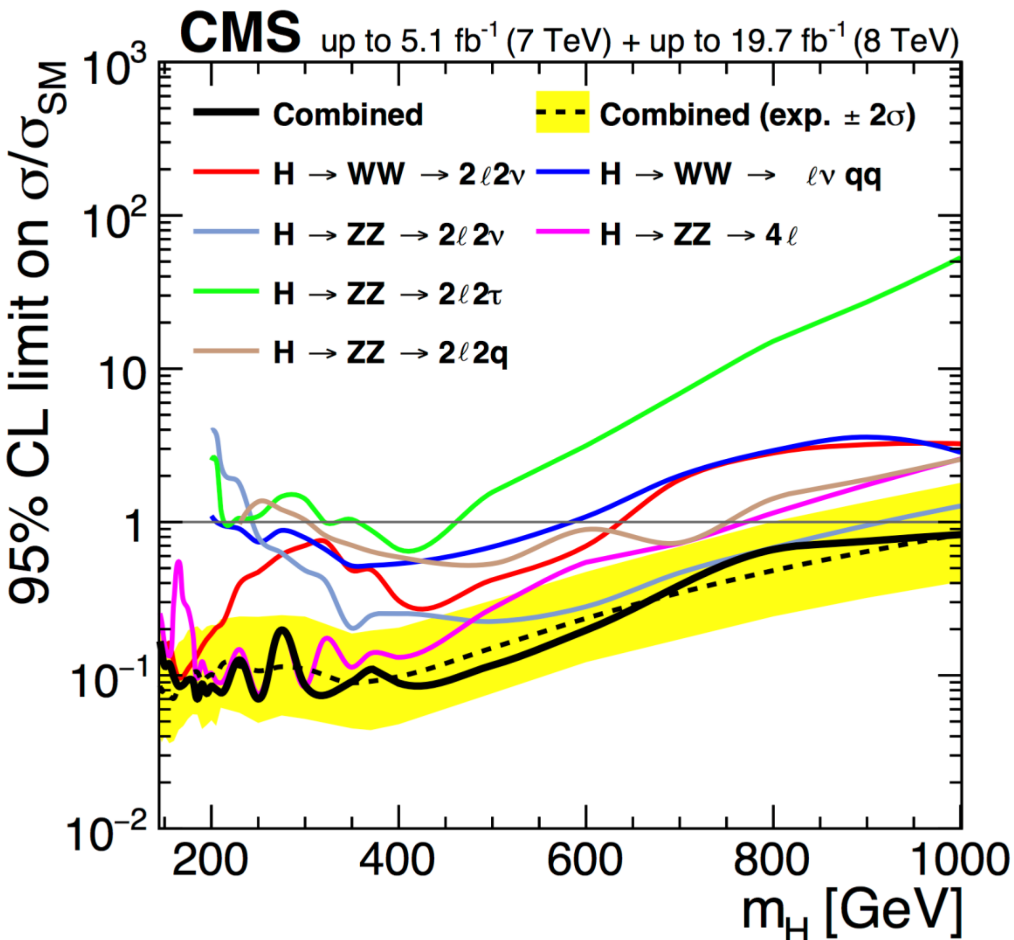
No (additional) excess found in the region from 65 to 600 GeV

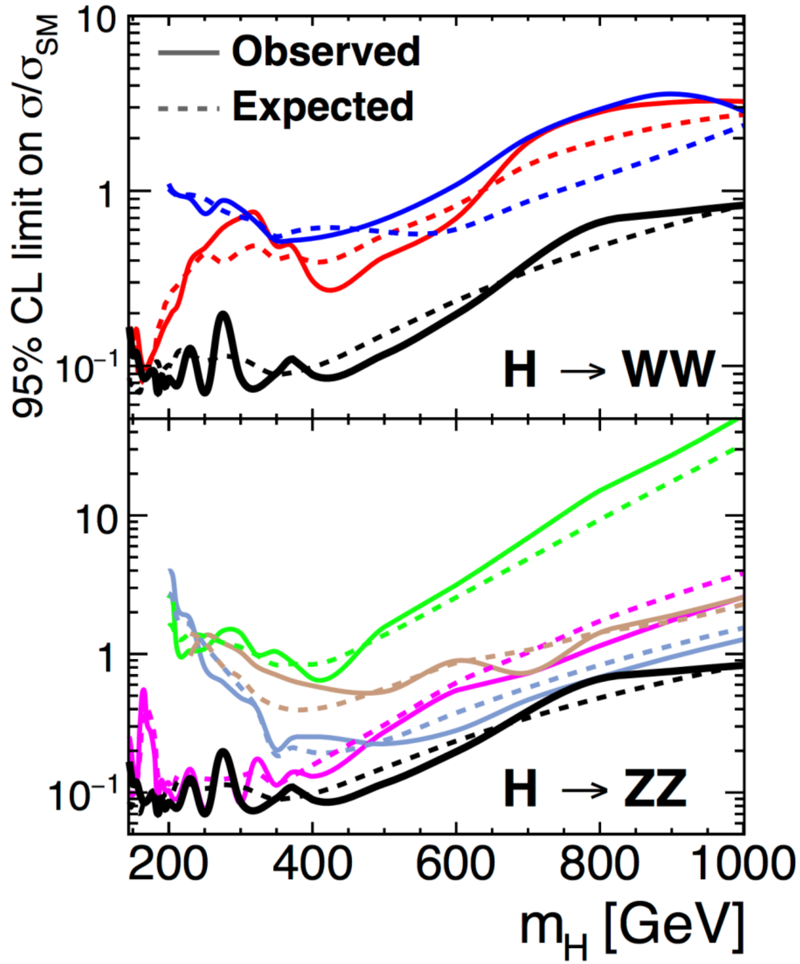


Phys. Rev. Lett. 113 (2014) 171801



High mass Higgs searches with SM channels WW or ZZ
Sensitivity reaches now up to ~ 1 TeV

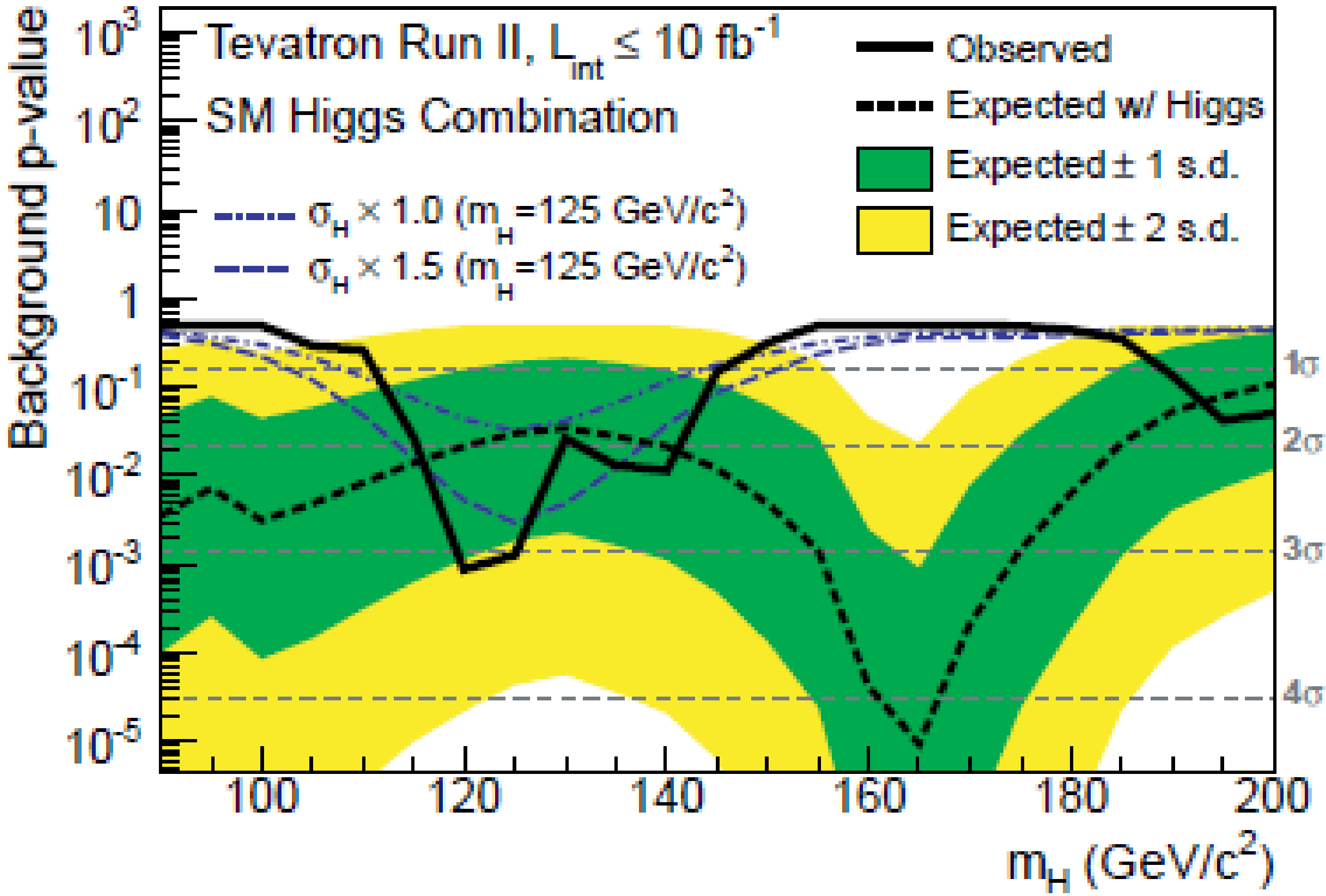




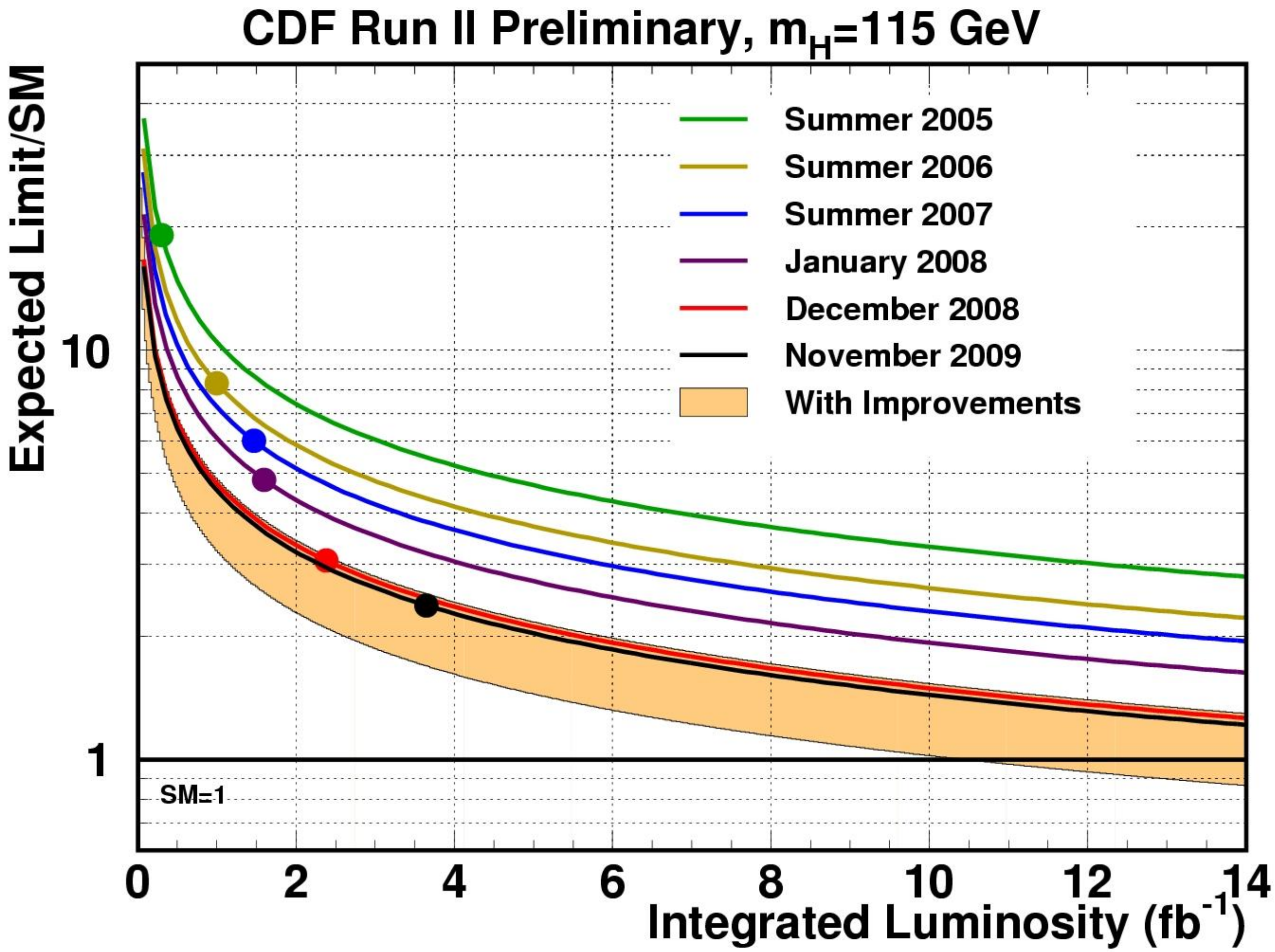
CMS arXiv:1504.00936v1[hep-ex] sub. to JHEP

The combined final TeVatron (CDF and D0) Higgs results

arXiv:1303.6346v3[hep-ex] and Phys. Rev. D88 (2013) 052014



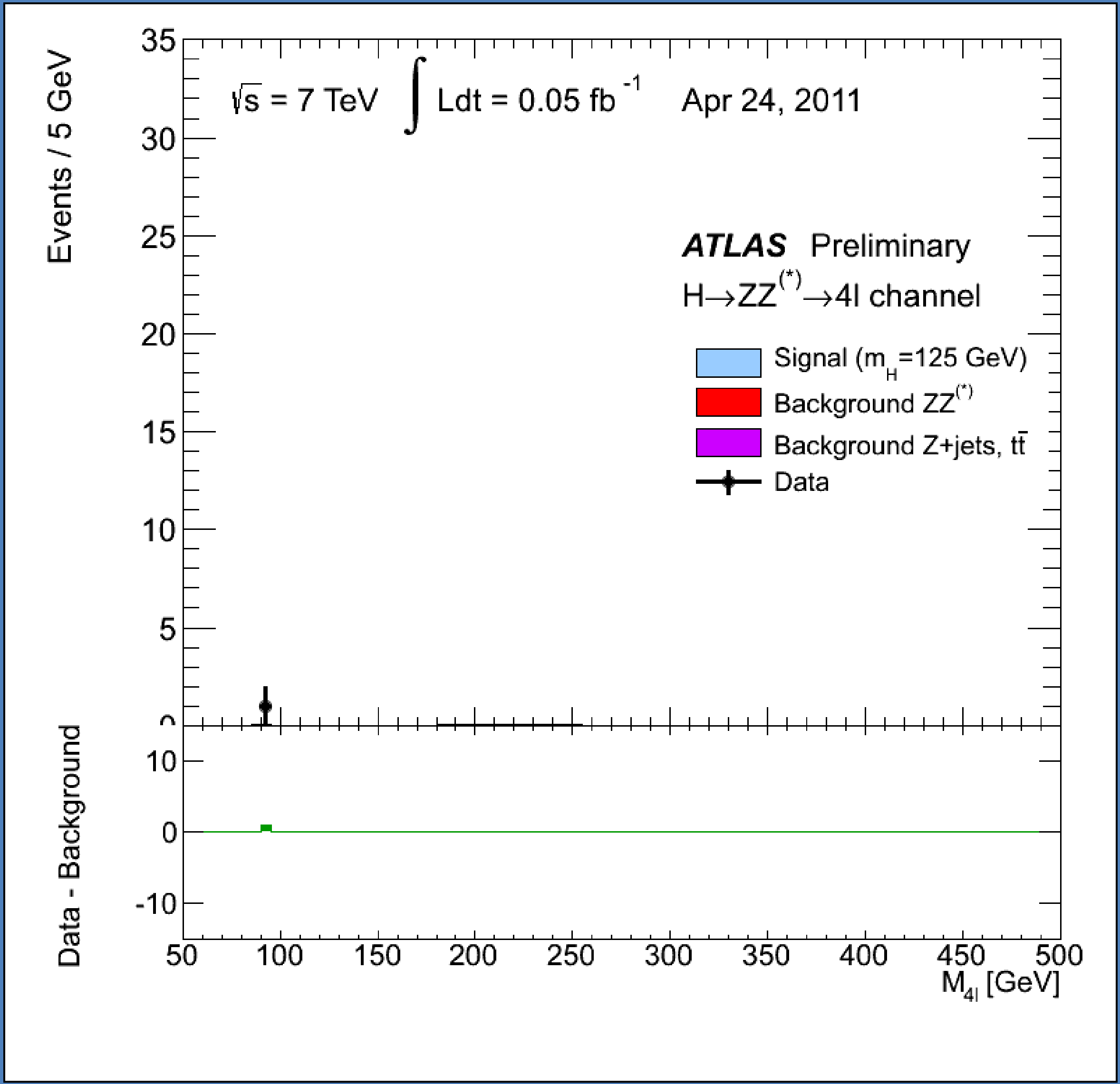
Observation of a 3 .0 standard deviation effect, consistent with the LHC signal



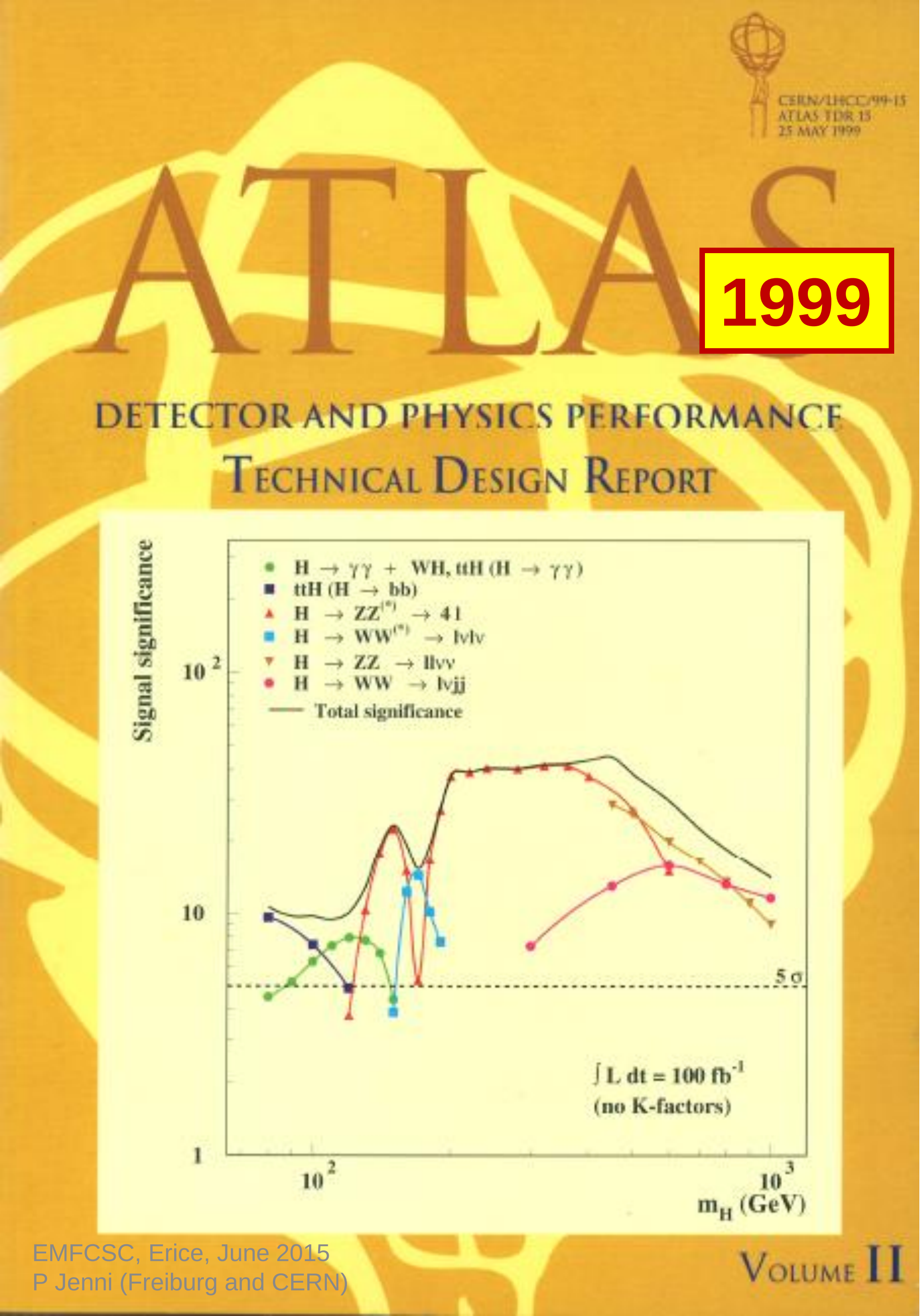
(for one experiment)

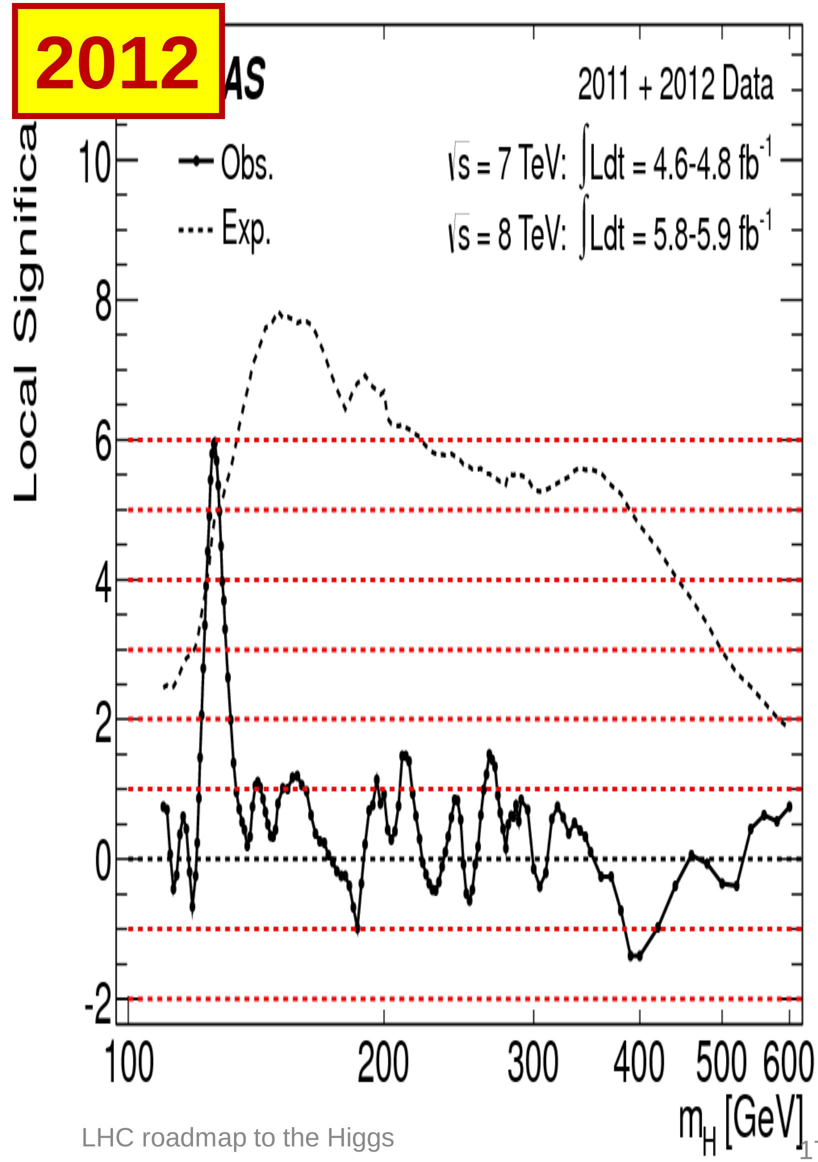
The TeVatron experiments reached that performance not only with the accumulated luminosity but also thanks to the remarkable progress in analysis methods over the years…

Birth and evolution of a signal: H→ 4l



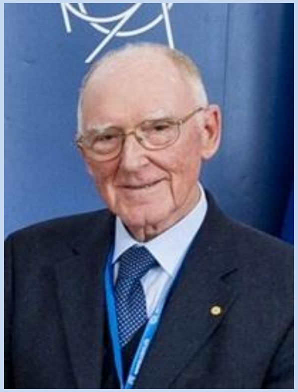
A dream becoming true much faster than anticipated long ago





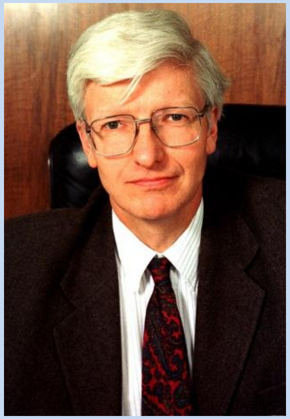
It was a very long road from first dreams to the fantastic scientific instrument we have now with the LHC and its experiments, and many visionaries deserve credit for it…

Herwig Schopper, CERN DG 1981 - 1988



Carlo Rubbia, CERN DG 1989 - 1993
Giorgio Brianti, first LHC Project Leader, until 1993

Sir Chris Llewellyn Smith, CERN DG 1994 - 1998
Lorenzo Foa († 2014), Research Director 1994 - 1998
Lyn Evans, LHC Project Leader 1994 - 2008



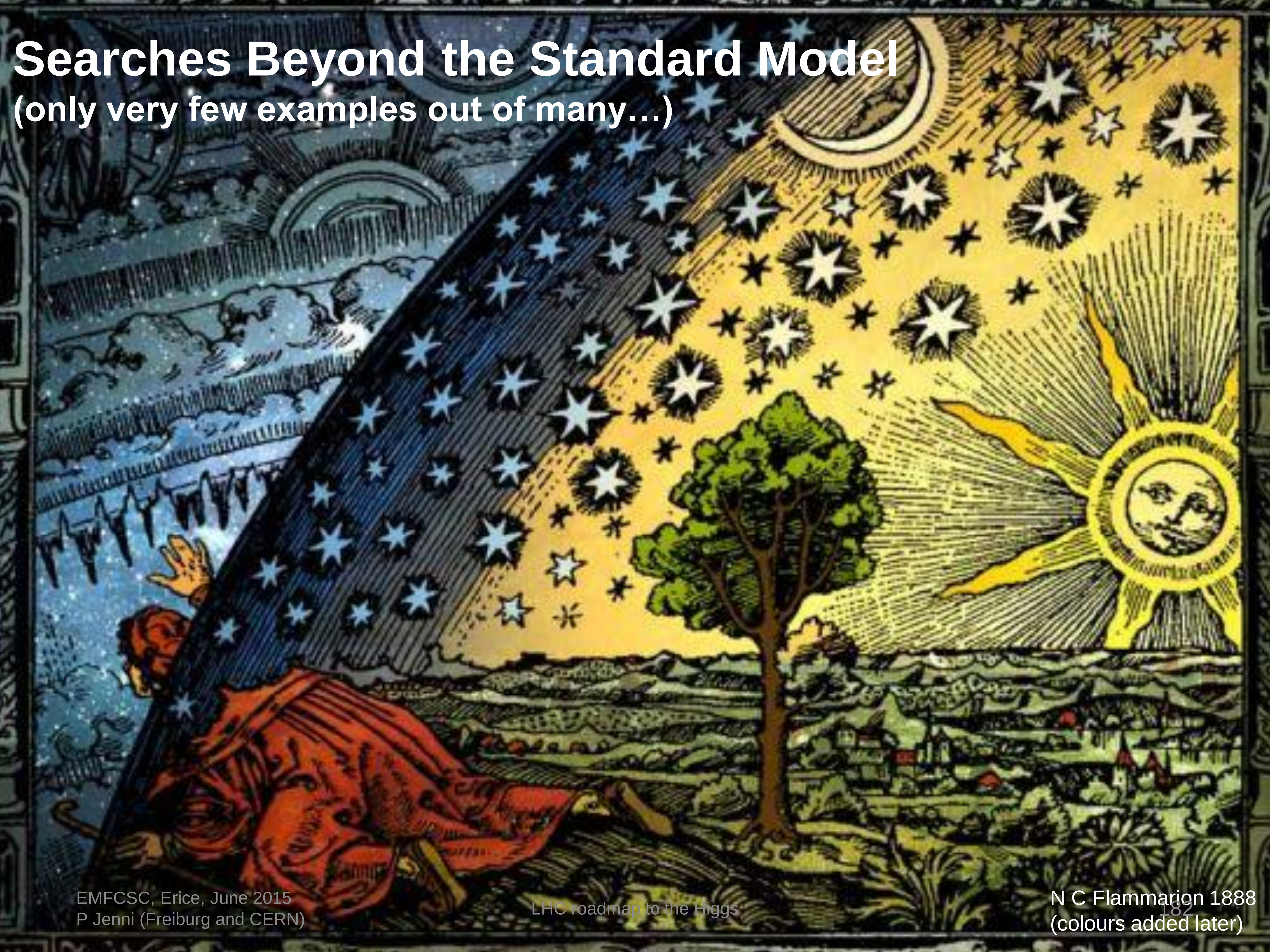
Luciano Maiani, CERN DG 1999 - 2003
Roger Cashmore, Research Director 1999 – 2003

Robert Aymar, CERN DG 2004 - 2008
Jos Engelen, Research Director 2004 - 2008

Rolf Dieter Heuer, CERN DG since 2009
Sergio Bertolucci, Research Director since 2009
Steve Myers, Director of Accelerators and Technology 2009 – 2013
(here shown together with the ATLAS and CMS Spokespersons Fabiola Gianotti and Joe Incandela, on the famous 4th July 2012)

Searches Beyond the Standard Model

(only very few examples out of many…)



N C Flammarion 1888
(colours added later)

Supersymmetry (SUSY)

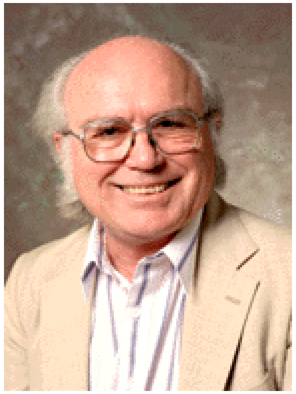
(Julius Wess and Bruno Zumino, 1974)

Establishes a symmetry between fermions (matter) and bosons (forces):

- Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2

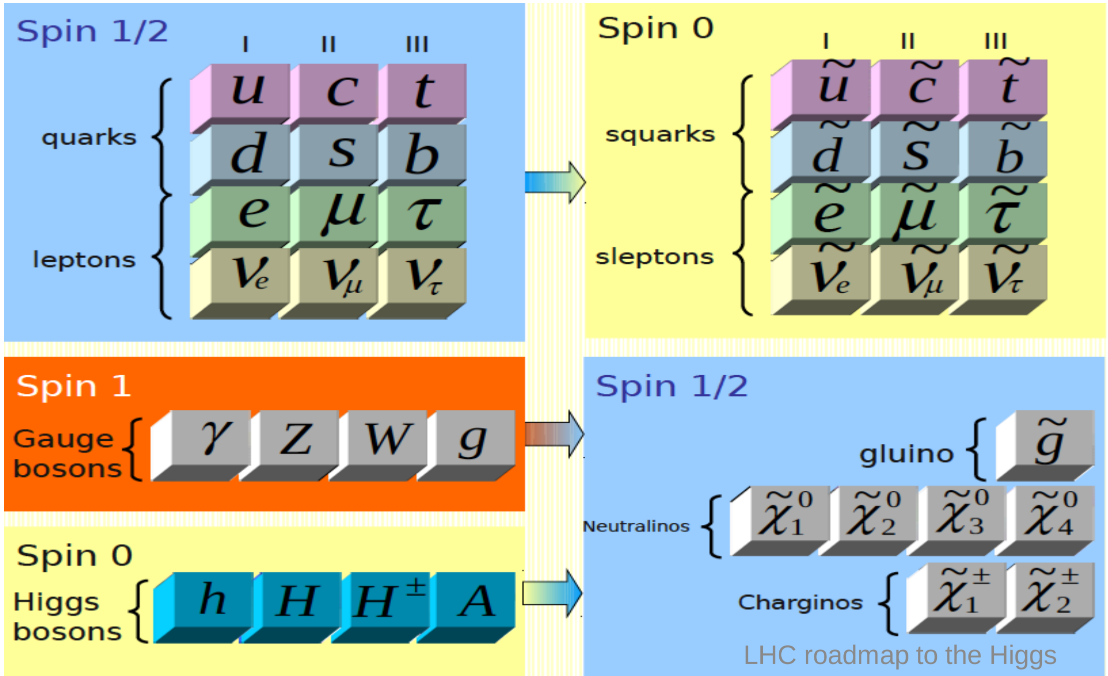
- Examples q (s=1/2) → $\tilde{q}$ (s=0) squark
g (s=1) → $\tilde{g}$ (s=1/2) gluino

Julius Wess (1934 – 2007)



Bruno Zumino (1923 – 2014)

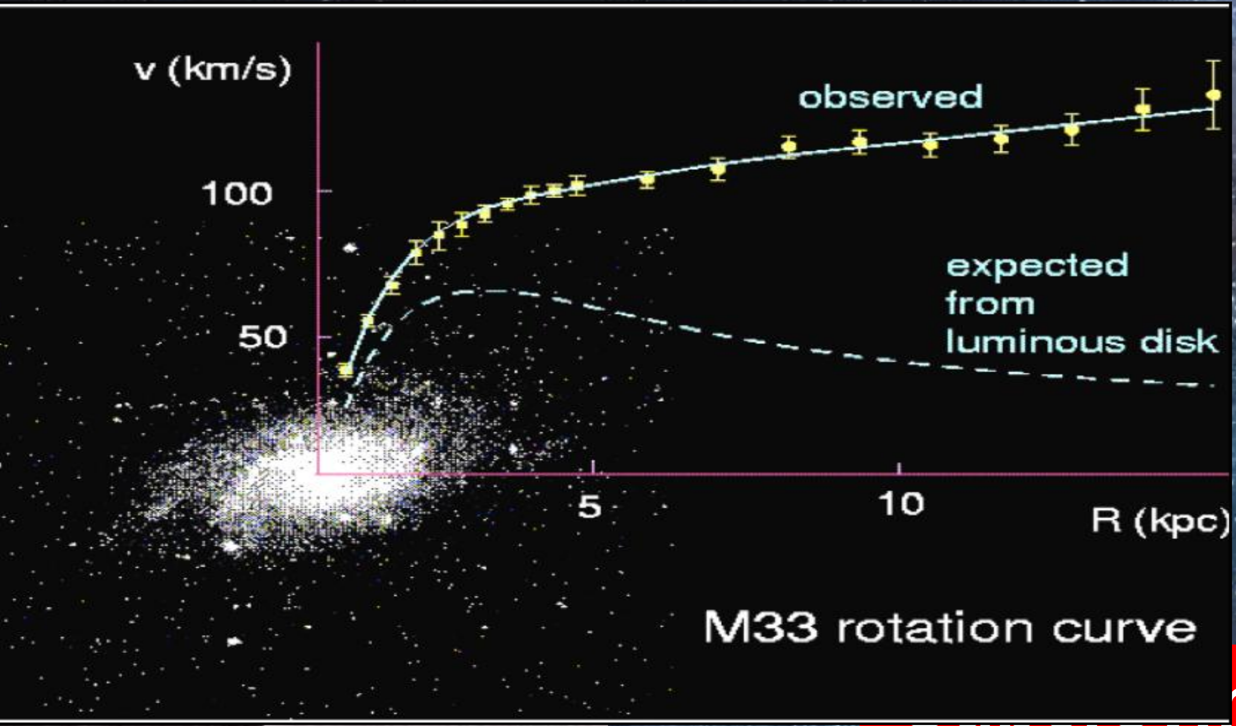
Our known world… **Maybe a new world?**



Motivation:

- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model

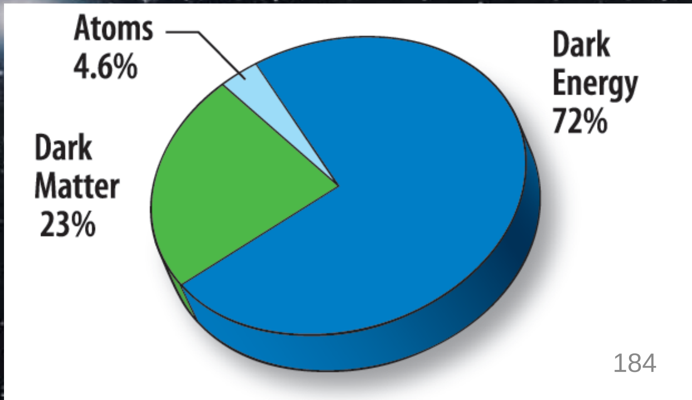
Dark Matter in the Universe



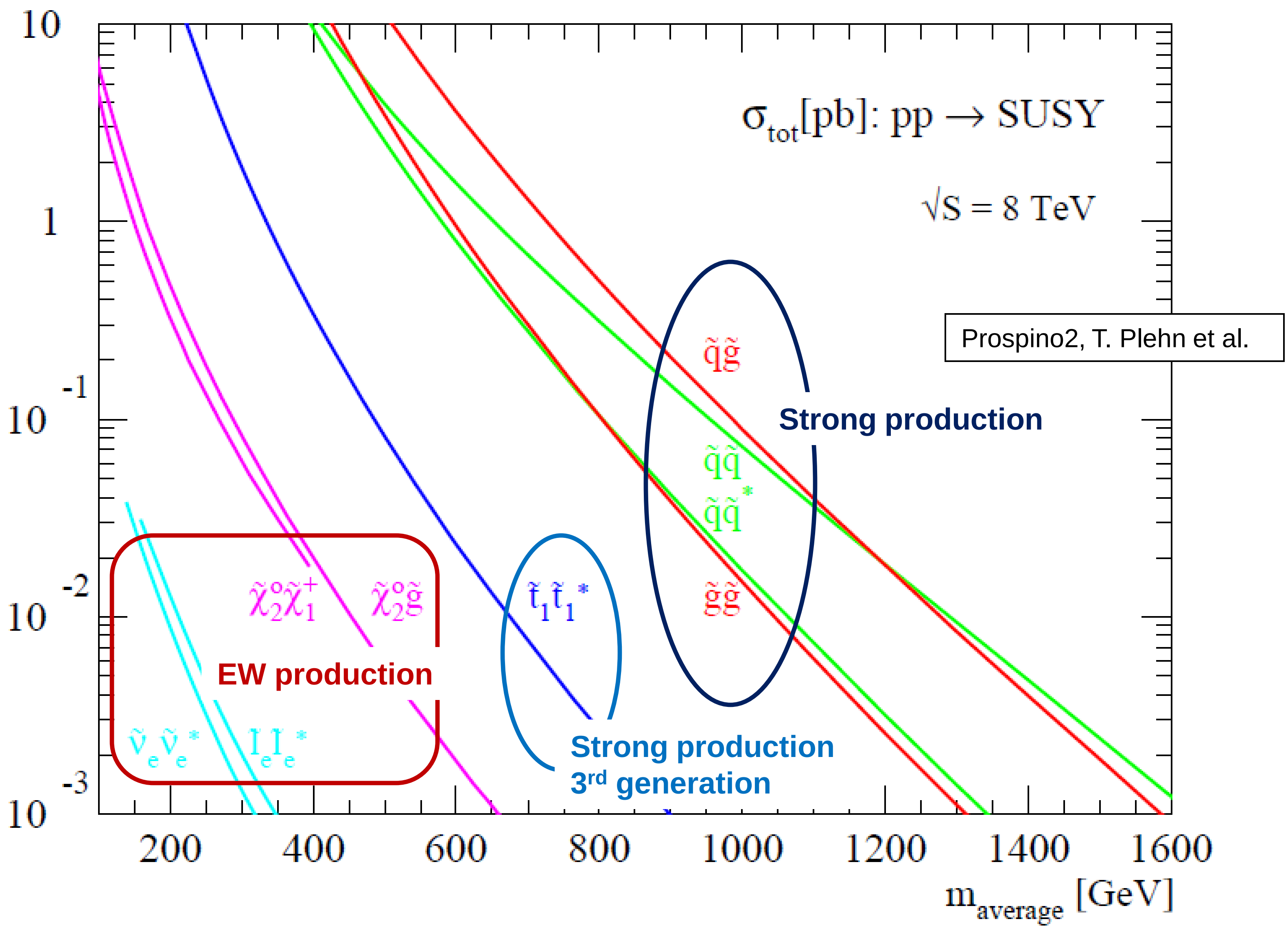
Vera Rubin ~ 1970

metric’ particles ?

F. Zwicky 1898-1974

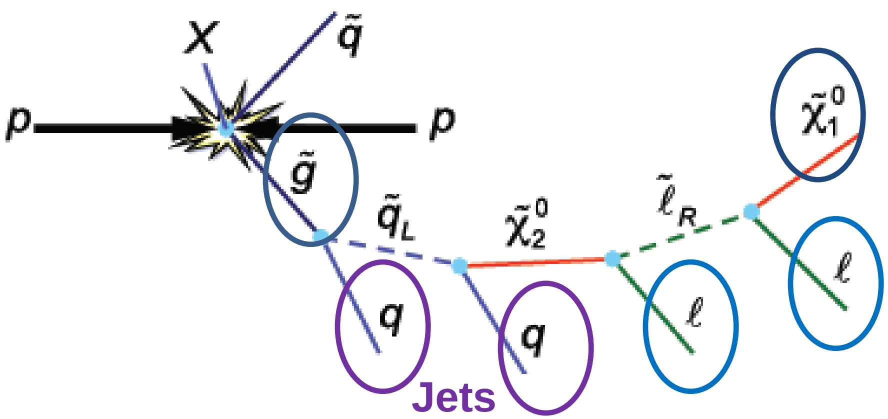


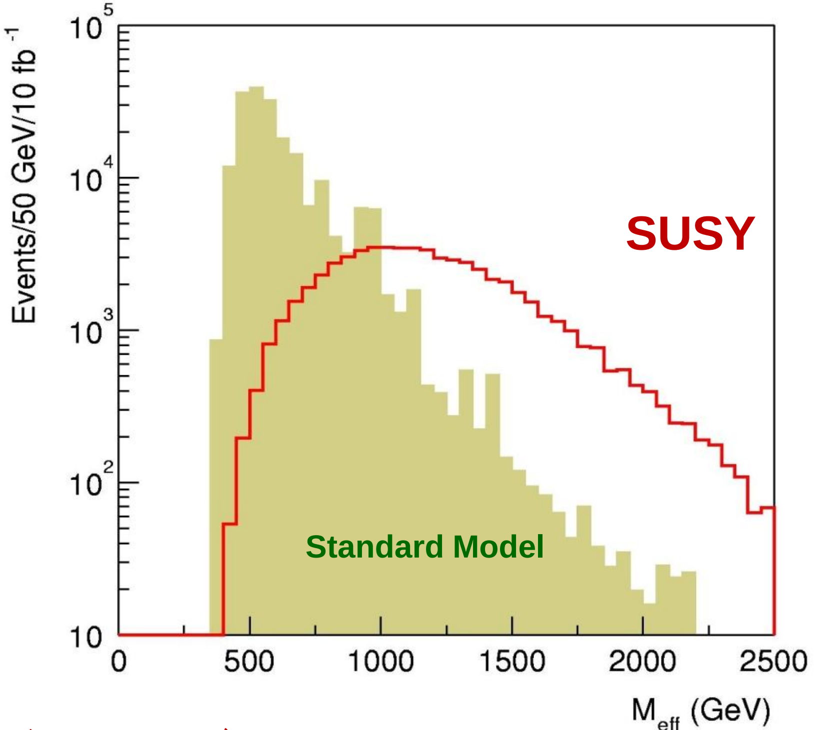
Expected production cross-sections at LHC



In practice SUSY searches at LHC are rather complicated

- Complex (and model-dependent) squark/gluino cascades





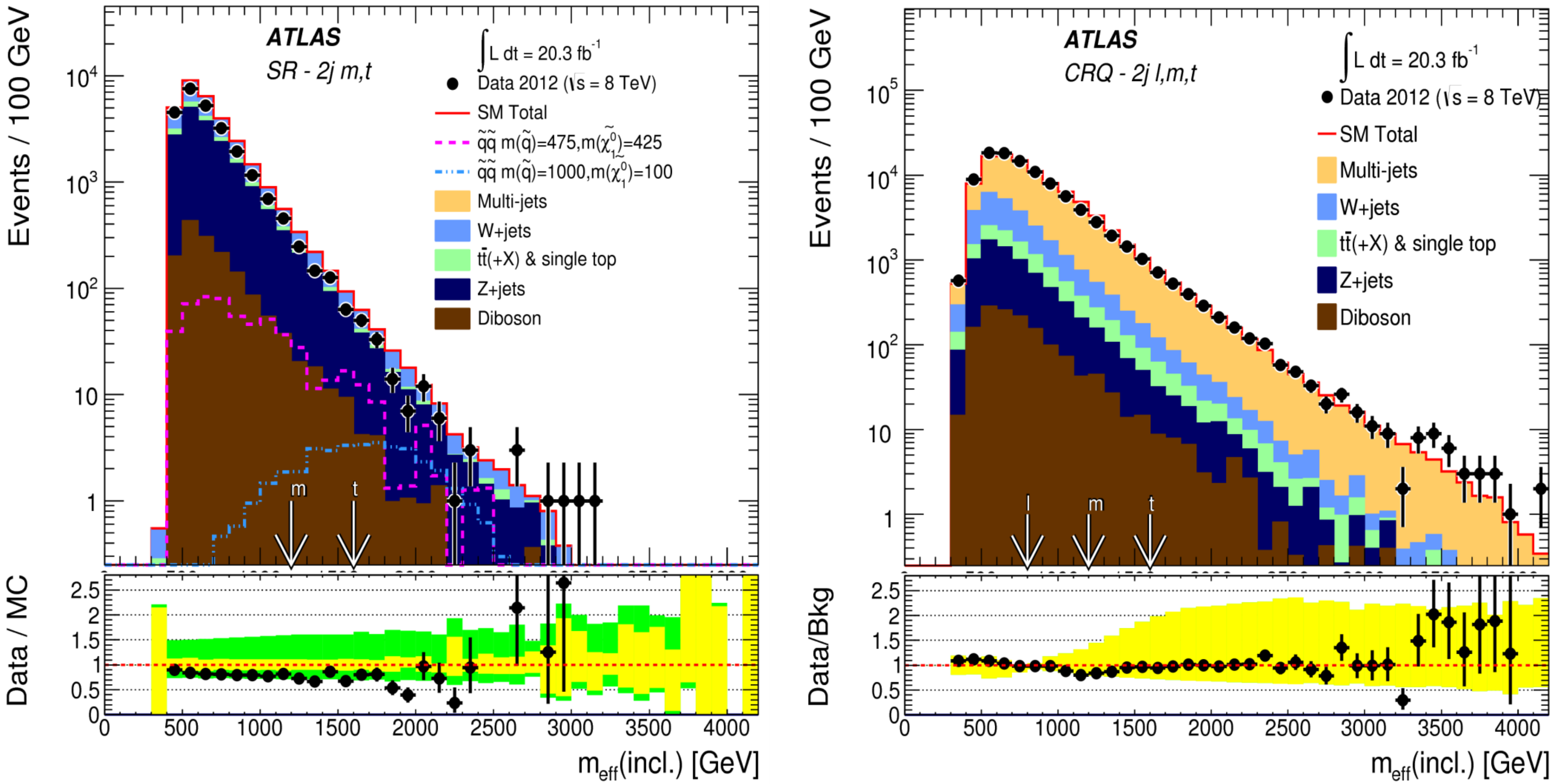
- Focus on signatures covering large classes of models while strongly rejecting SM background
  - large missing E_T
  - High transverse momentum jets
  - Leptons
    - Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)
  - B-jets: to enhance sensitivity to third-generation squarks
  - Photons: typically for models with the gravitino as LSP

Meff = Etmiss + Σ pT(jets)

A random example from the 2012 data, to show the principle

0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)

JHEP 09 (2014) 176

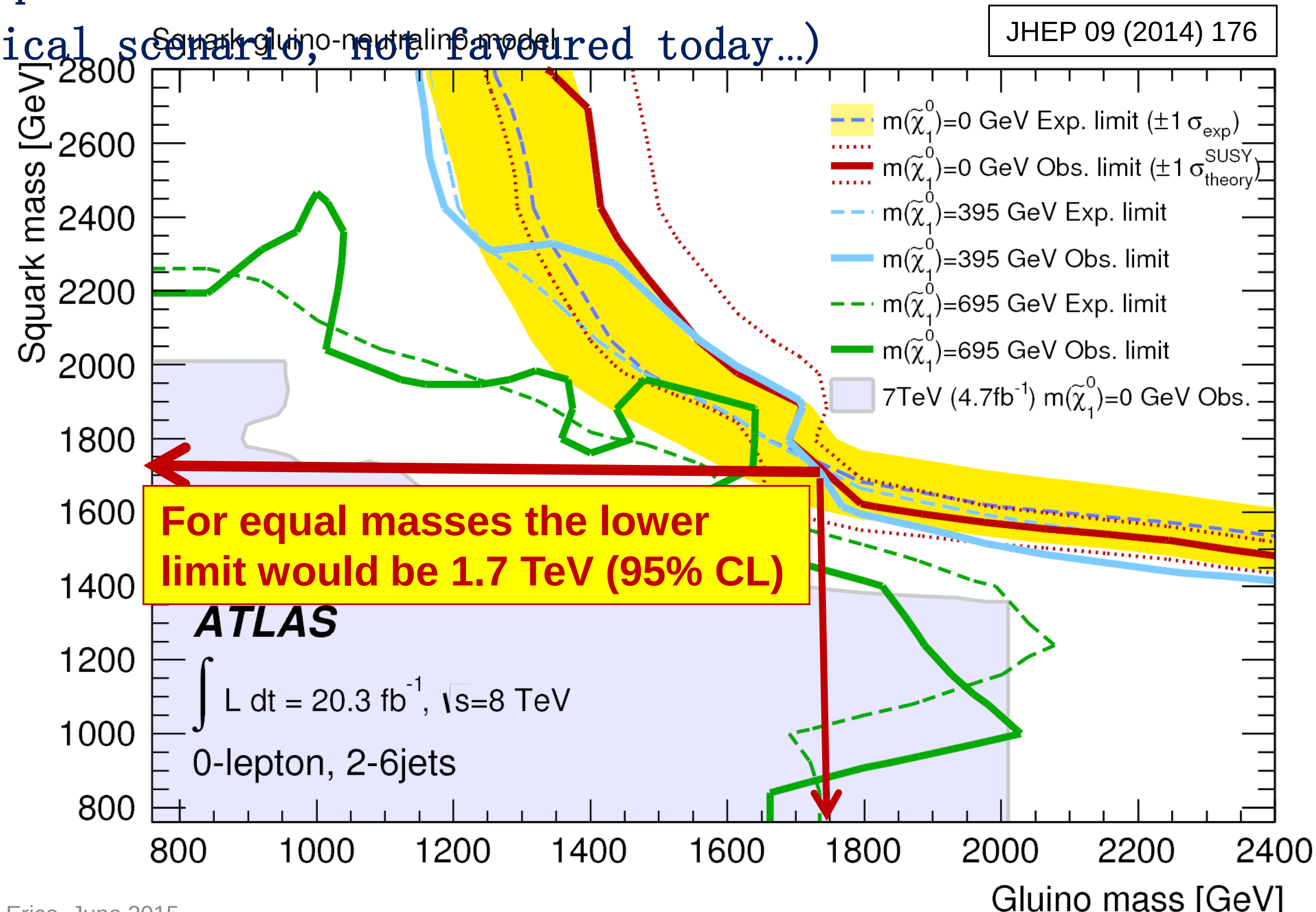


A signal region

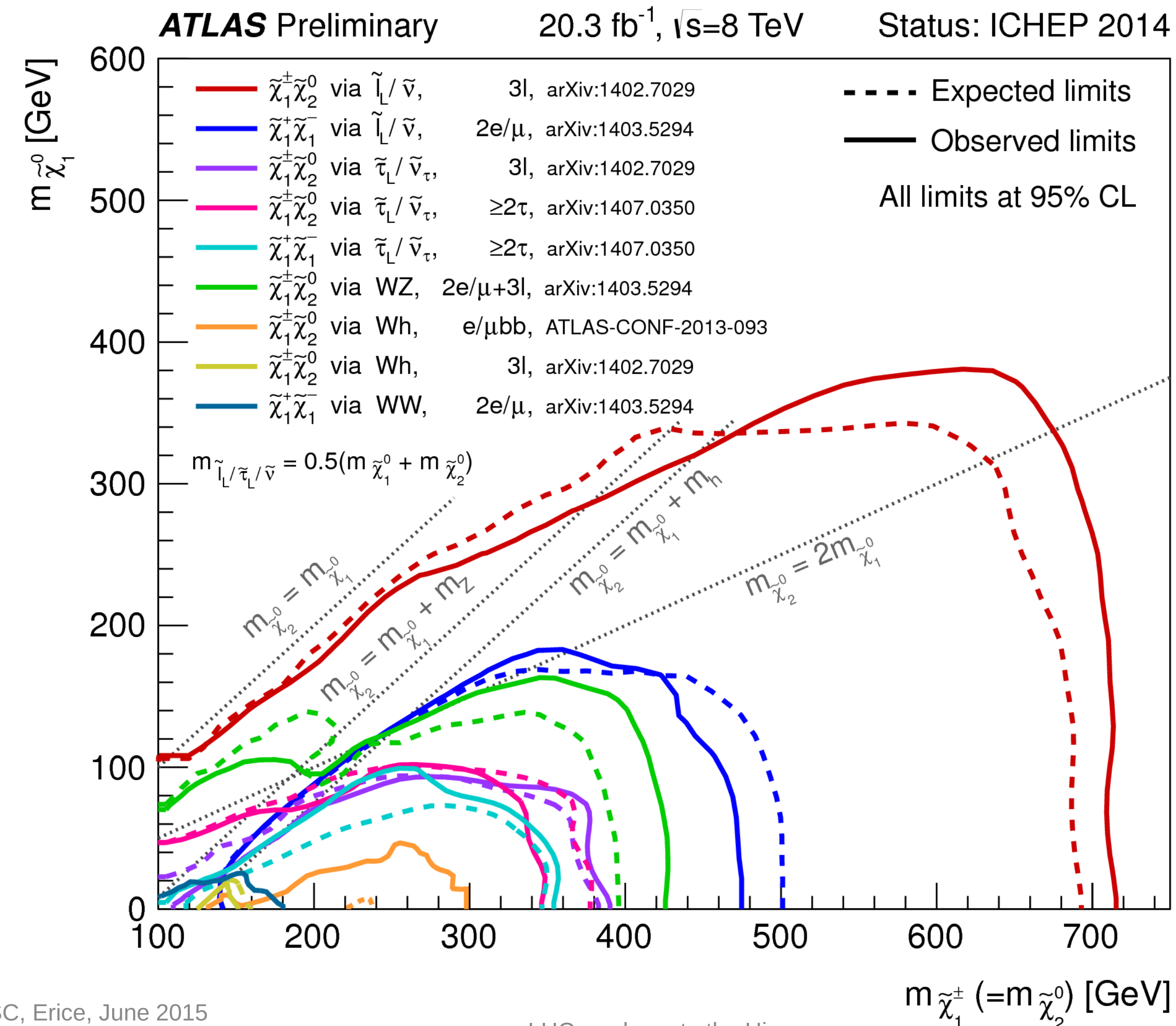
A control region where no signal is expected

Interpretation of the results

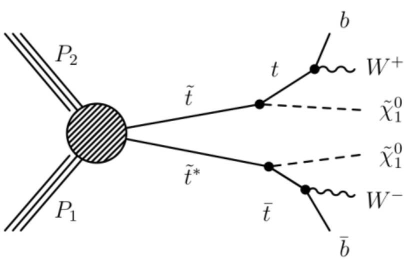
Example: phenomenological MSSM models containing only squarks of the 1st and 2nd generation, gluino and light neutralinos (the simple classical scenario, not favoured today…)

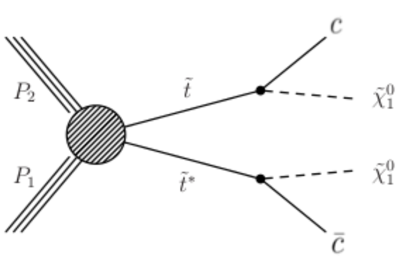


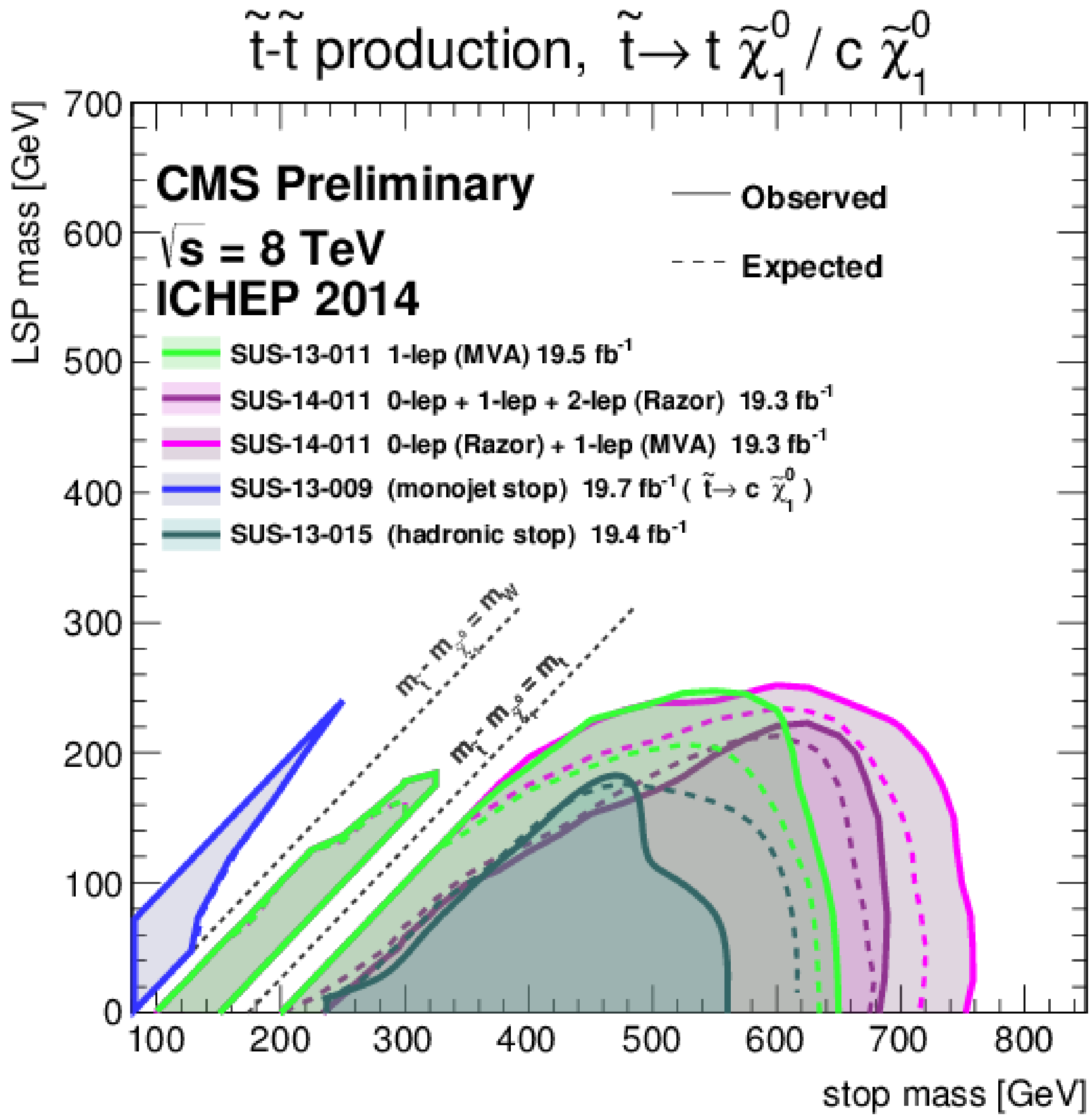
Example of chargino and neutralino limits from electroweak productions



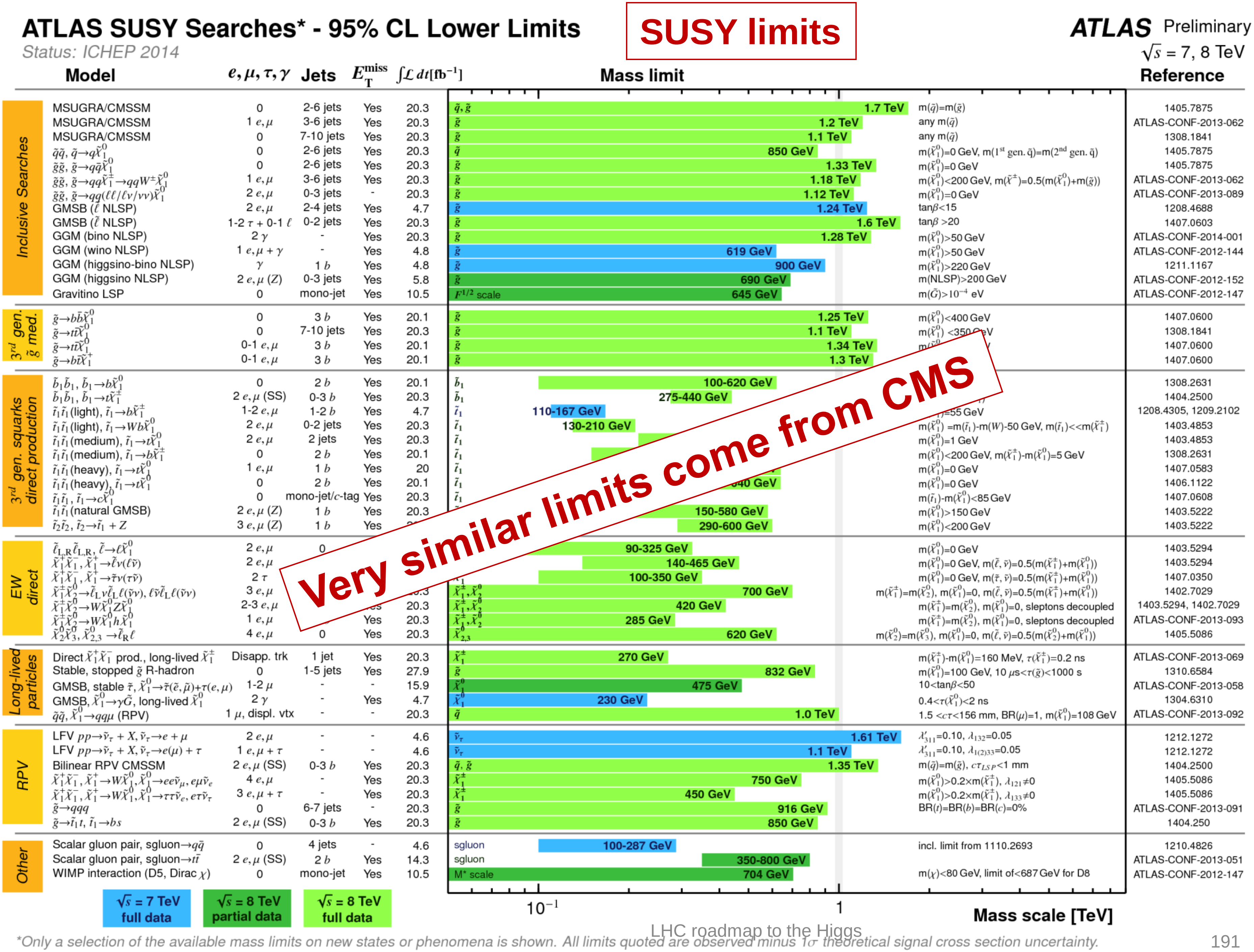
Example of limits for stop pair production







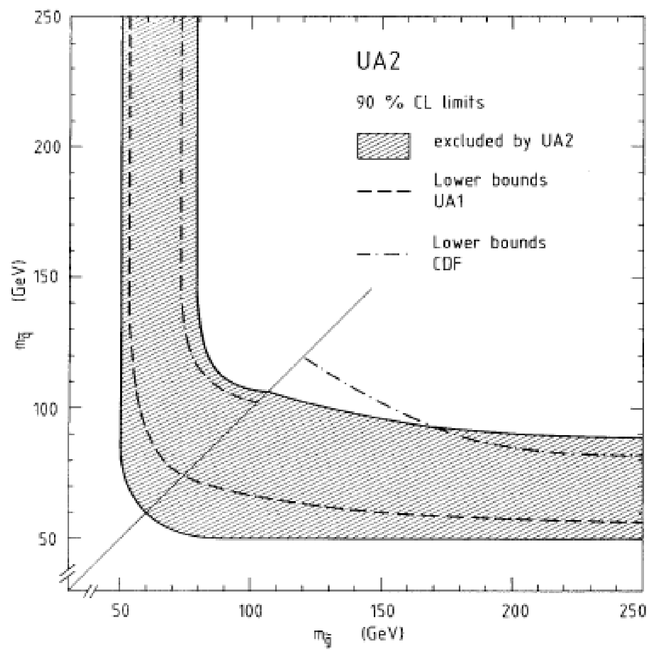
SUSY limits



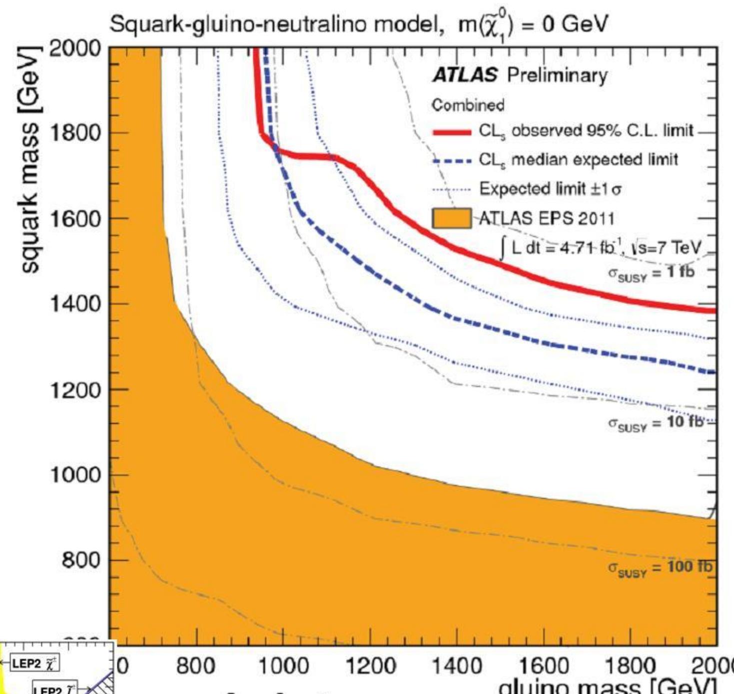
Very similar limits come from CMS

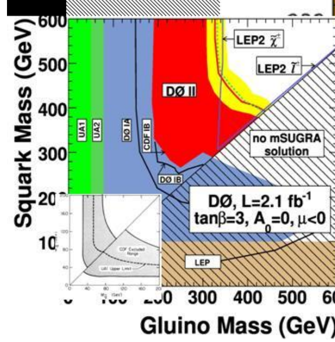
Our theory friends predicted since long ‘SUSY just around the corner…’

First attempt with the upgraded UA2 experiment at the CERN $p\bar{p}$

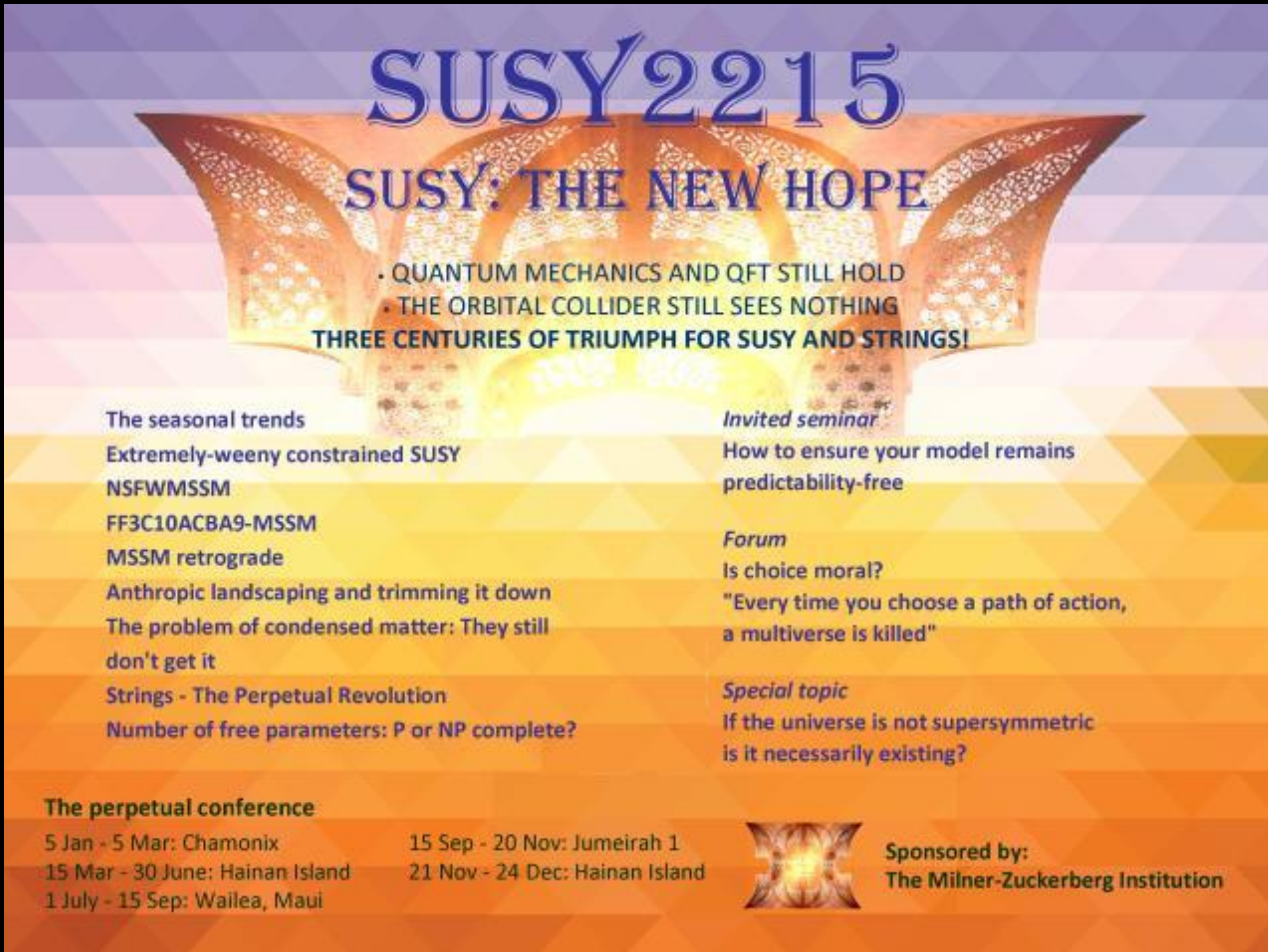


Phys. Lett. B235 (1990) 363

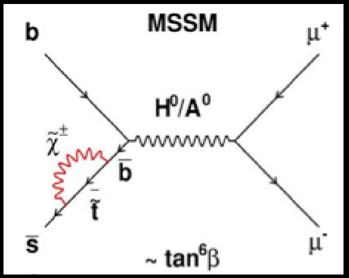


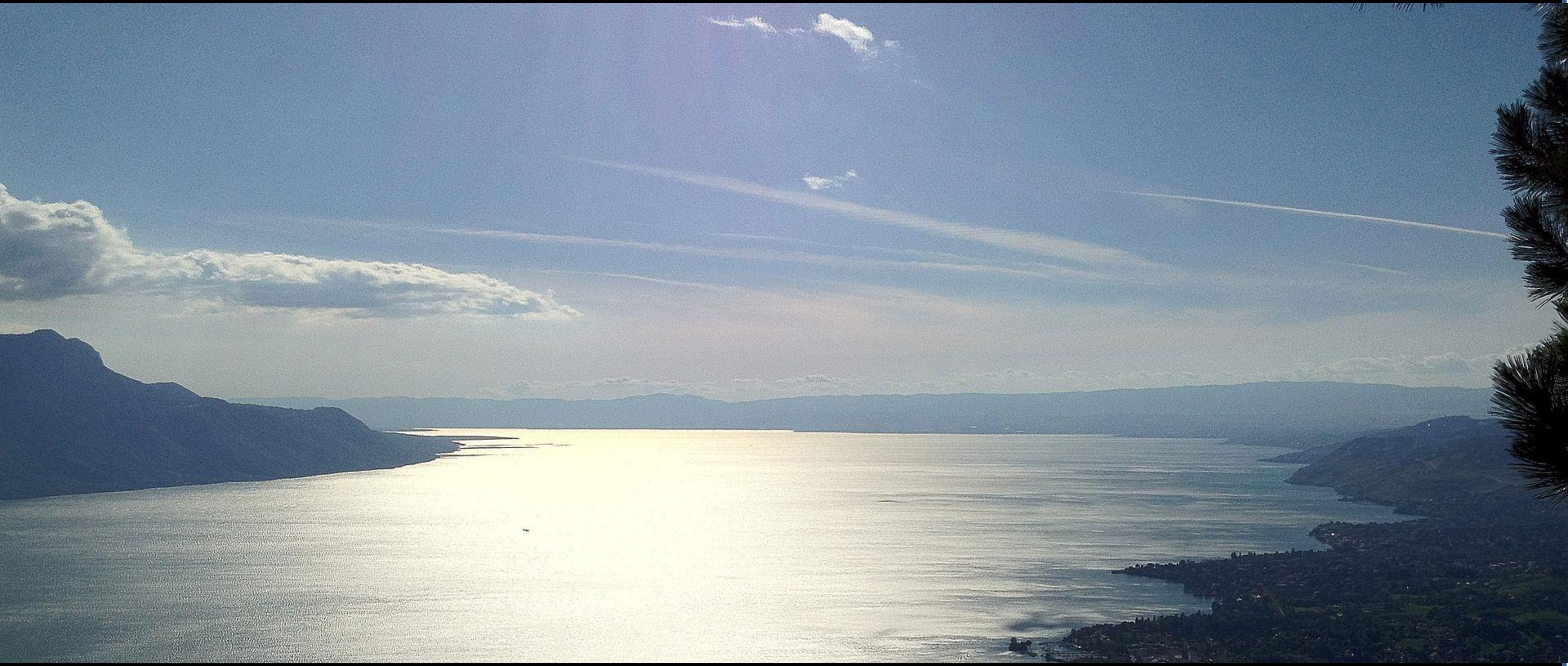


From the TeVatron to LHC Run-1


SUSY2215
SUSY: THE NEW HOPE
· QUANTUM MECHANICS AND QFT STILL HOLD
· THE ORBITAL COLLIDER STILL SEES NOTHING
THREE CENTURIES OF TRIUMPH FOR SUSY AND STRINGS!
The seasonal trends
Extremely-weeny constrained SUSY
NSFWMSSM
FF3C10ACBA9-MSSM
MSSM retrograde
Anthropic landscaping and trimming it down
The problem of condensed matter: They still don't get it
Strings - The Perpetual Revolution
Number of free parameters: P or NP complete?
Invited seminar
How to ensure your model remains predictability-free
Forum
Is choice moral?
"Every time you choose a path of action, a multiverse is killed"
Special topic
If the universe is not supersymmetric is it necessarily existing?
The perpetual conference
5 Jan - 5 Mar: Chamonix
15 Mar - 30 June: Hainan Island
1 July - 15 Sep: Wailea, Maui
15 Sep - 20 Nov: Jumeirah 1
21 Nov - 24 Dec: Hainan Island
Sponsored by:
The Milner-Zuckerberg Institution

First signs of new physics could also come from accurate measurements of clean processes for which the Standard Model makes very precise predictionsthe known SM processes are at play



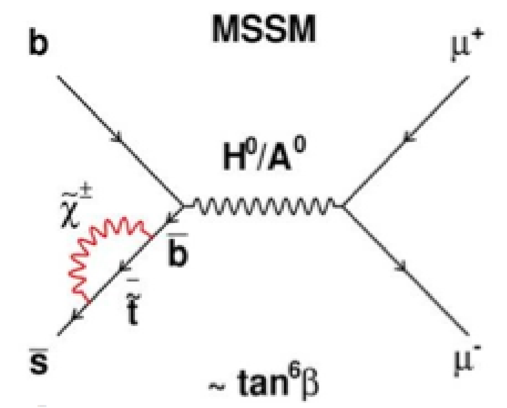


Measured deviations could indicate that something more than just the known SM processes are at play

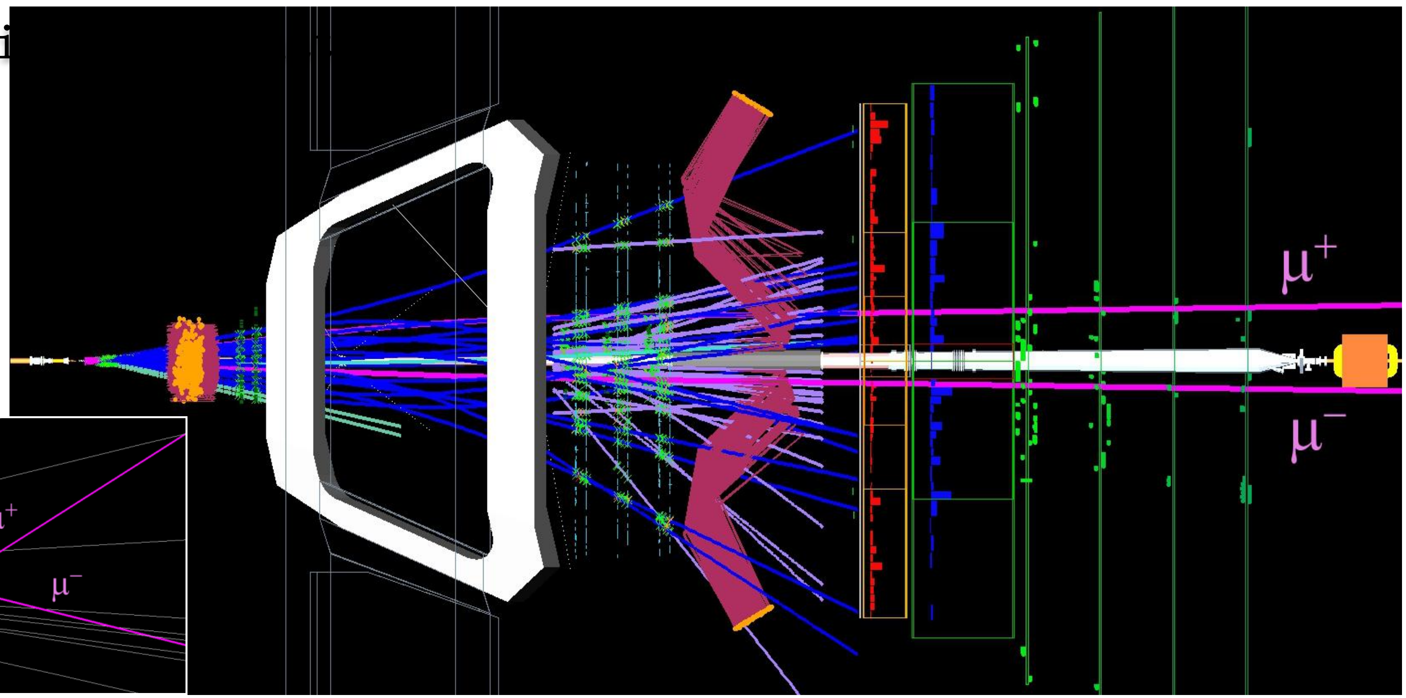
The search for $B_{s\ (d)} \rightarrow \mu\mu$

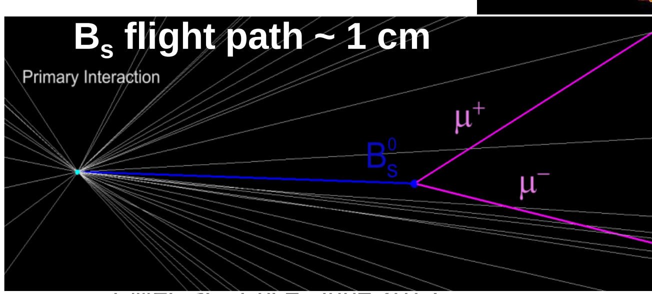
Very rare decay sensitive to New Physics
(in particular to models with high *tan β*)

Precise predictions in SM:
$BR(B_s \rightarrow \mu\mu) = 3.56 \pm 0.30 \times 10^{-9}$
$BR(B_d \rightarrow \mu\mu) = 1.07 \pm 0.10 \times 10^{-10}$



Very clean experi





The search for $B_{s\ (d)} \rightarrow \mu\mu$

LHCb Phys. Rev. Lett. 110 (2013) 101805

CMS Phys. Rev. Lett. 111 (2013) 101804

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(in particular to models with high *tan β*)

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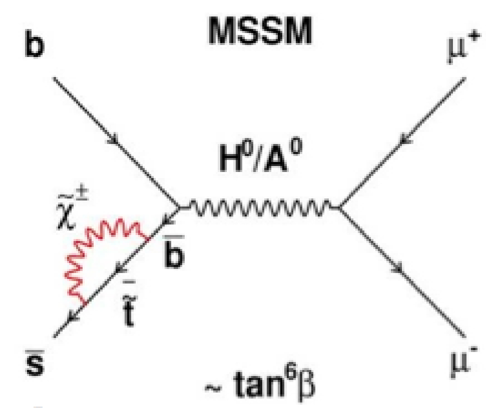
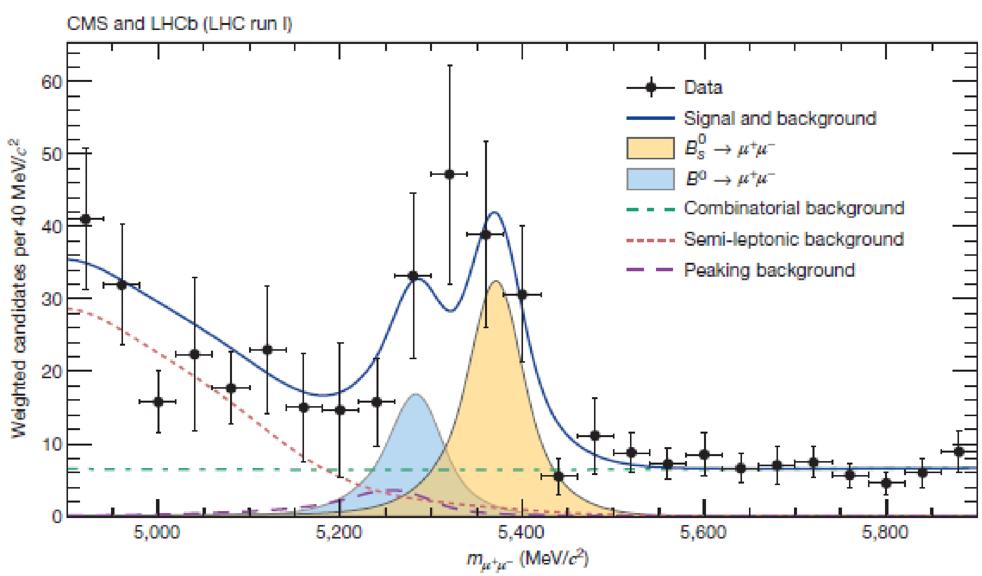


Measured with the full data sets of LHCb and CMS, and a common simultaneous fit

$BR(B_s \rightarrow \mu\mu) = 2.8\,^{+0.7}_{-0.6} \times 10^{-9}$

$BR(B \rightarrow \mu\mu) = \mathbf{3.9}\,^{+1.6}_{-1.4} \times 10^{-10}$

In good agreement with the SM prediction within the present measurement errors

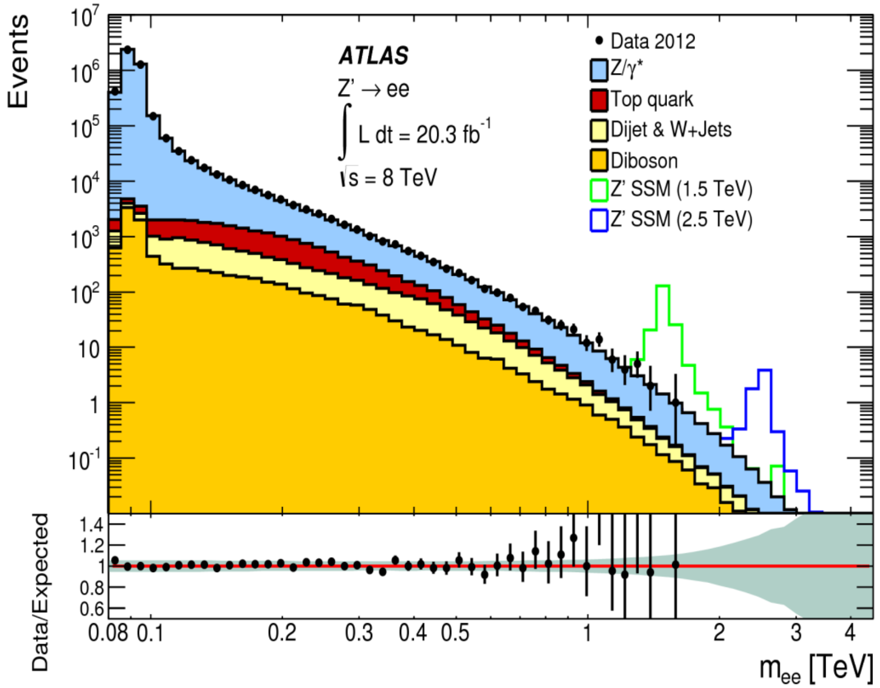


LHCb+CMS, Nature Letter doi:10.1038/nature 14474

Searches for heavy W and Z like particles

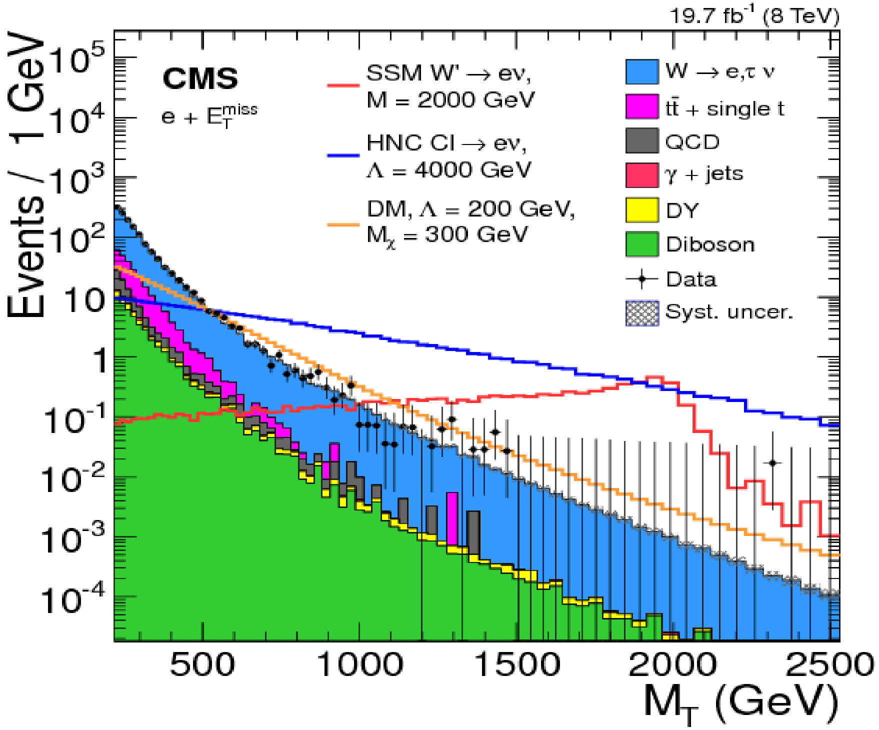
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z': Di-lepton pairs



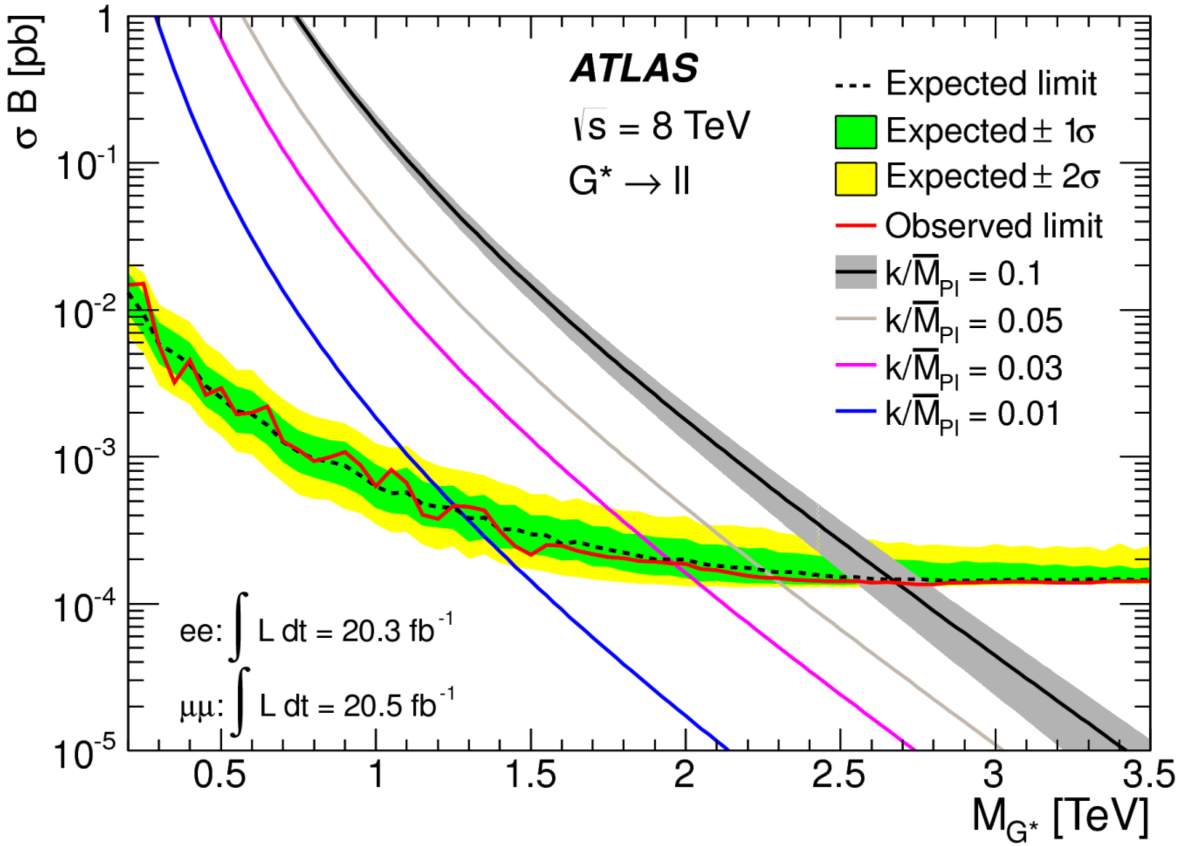
Phys. Rev. D 90 (2014) 052005

W': Lepton + ETmiss



arXiv:1408.2745v1[hep-ex] sub. to Phys. Rev. D

Lower mass limits, at 95% CL, for spin-2 Randall-Sundrum Gravitons

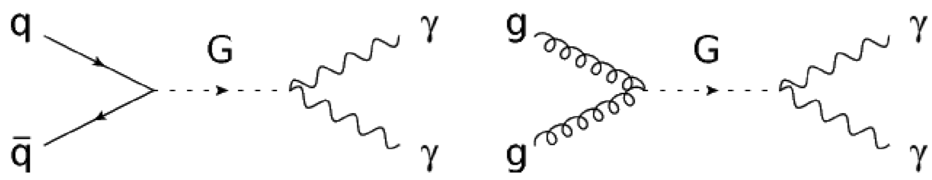


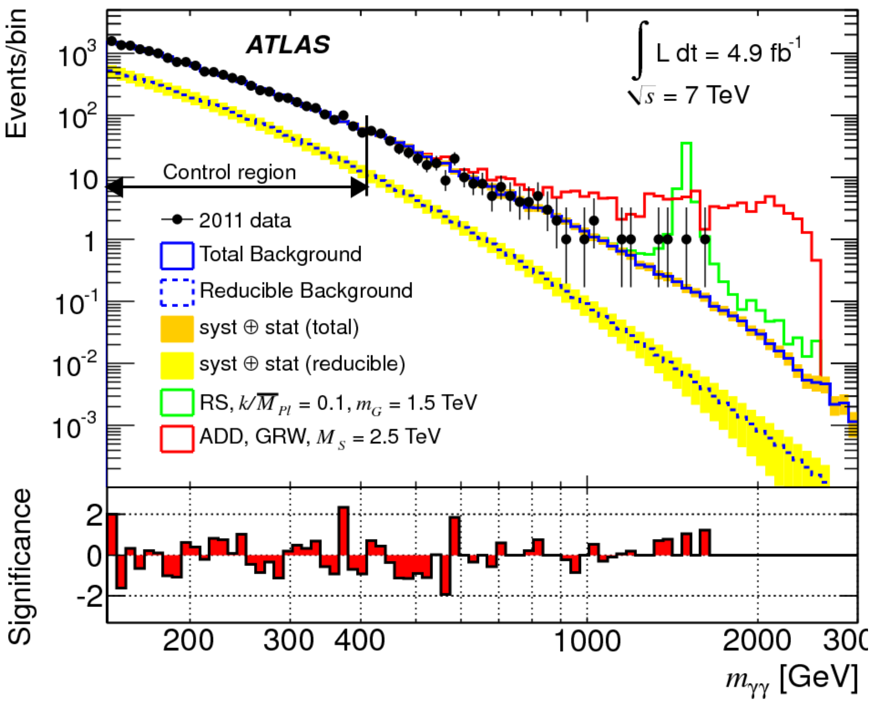
Phys. Rev. D 90 (2014) 052005

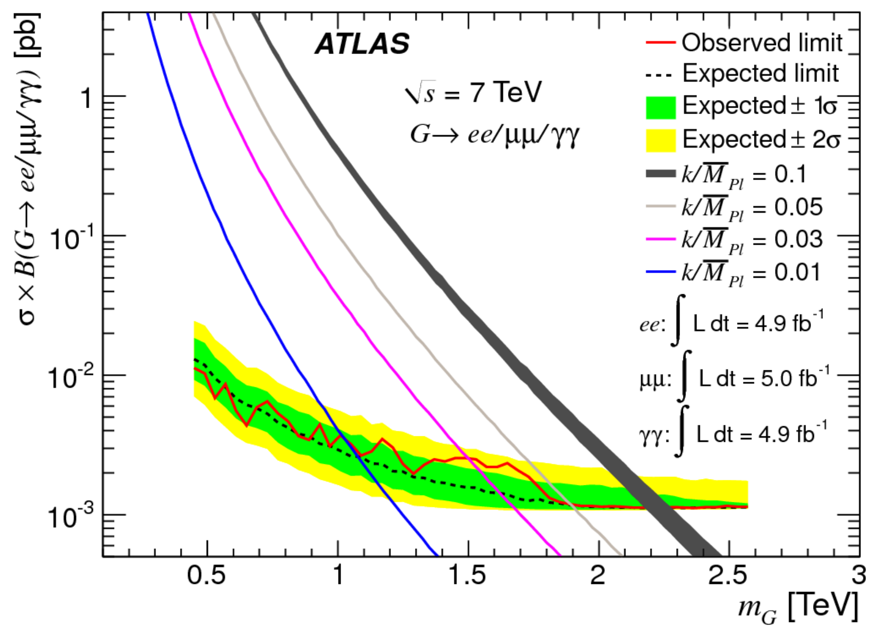
R Sundrum
L Randall
F Gianotti

New particles decaying into two photons

Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)



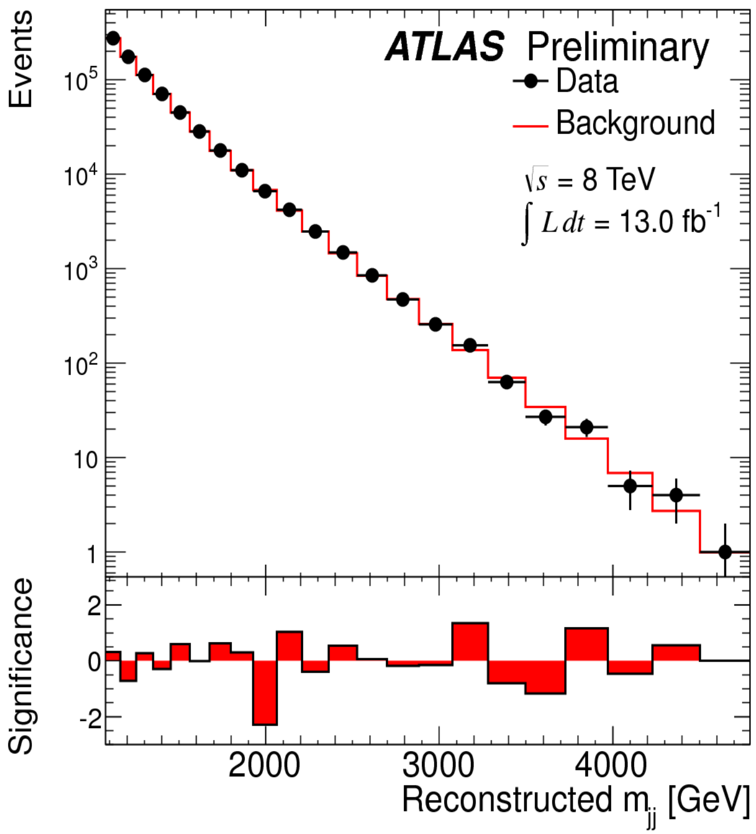




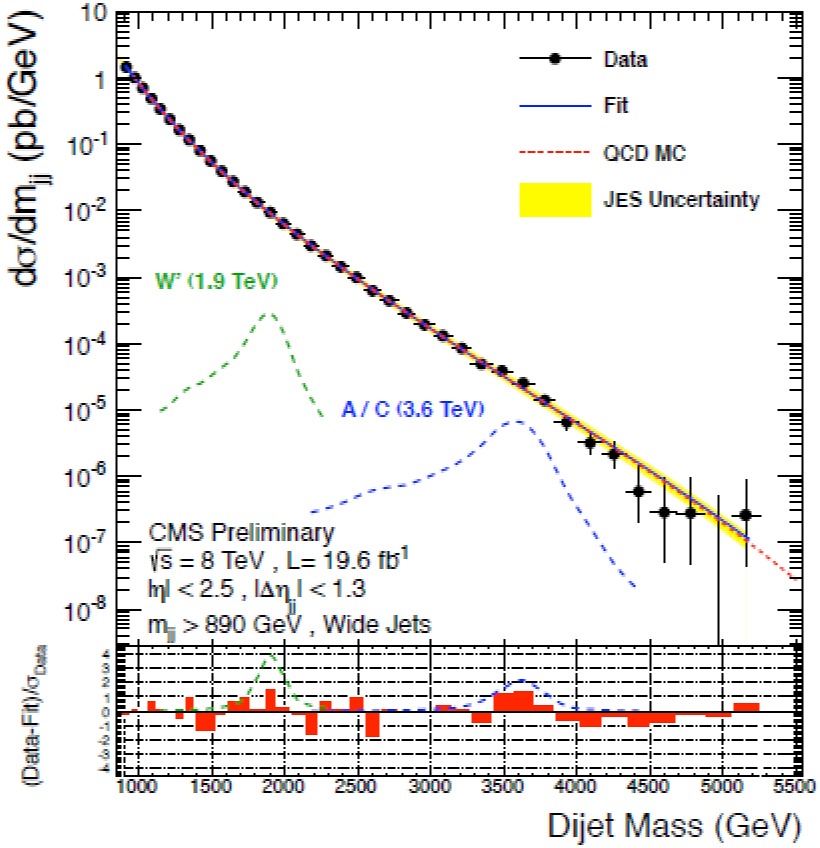
New J Phys 15 (2013) 043007

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum



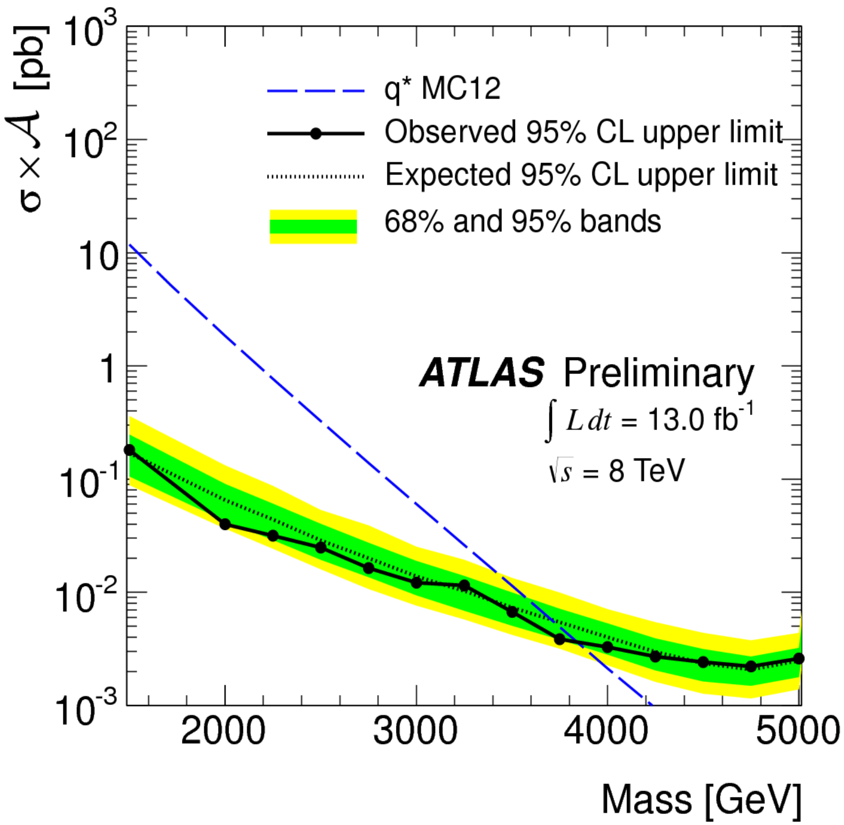
ATLAS-CONF-2012-148

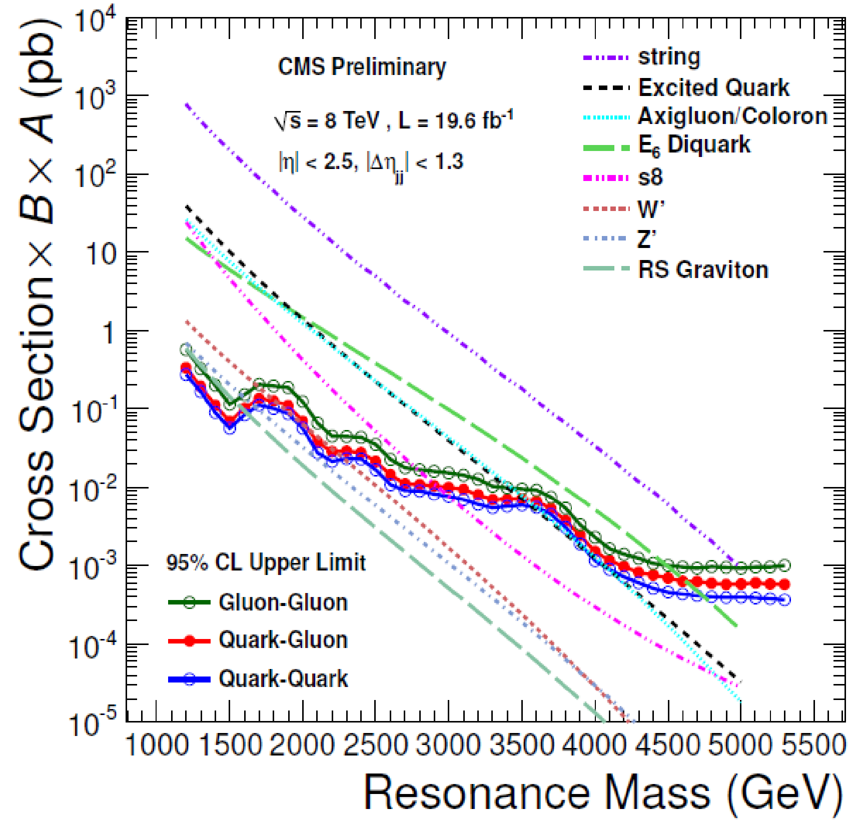


CMS-EXO-12-059

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

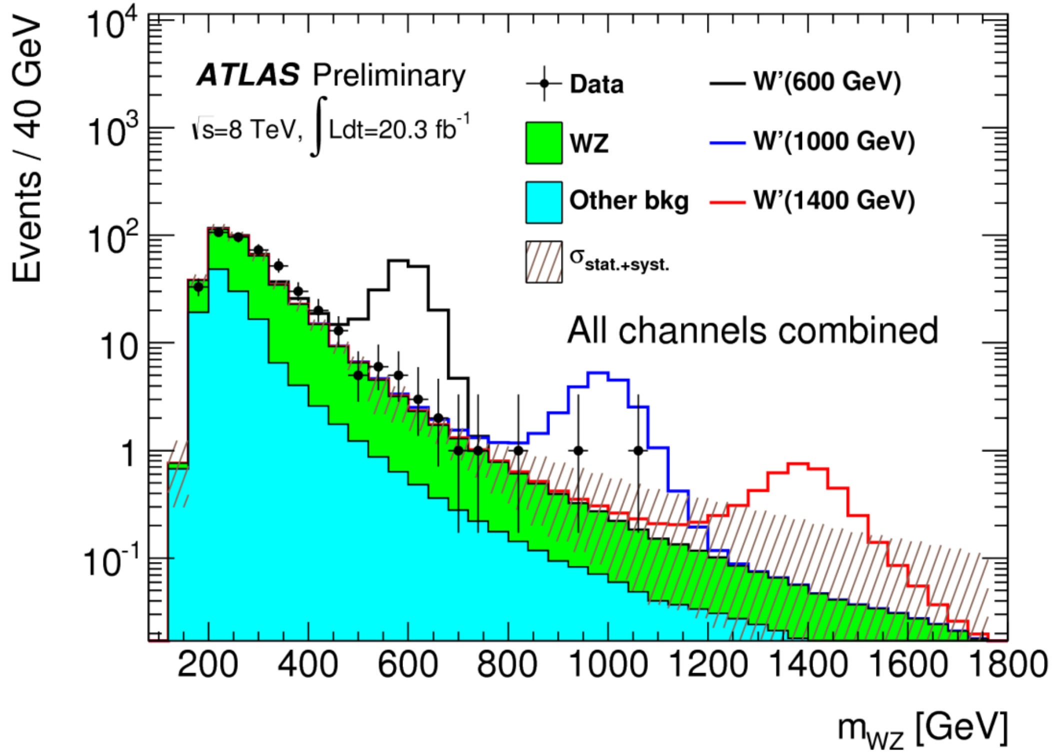
Search for resonances in the di-jet mass spectrum





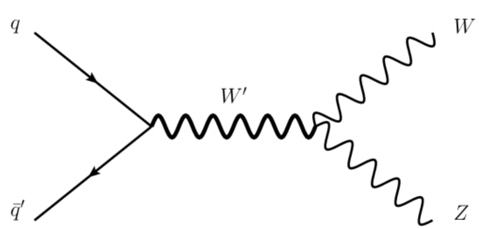
ATLAS-CONF-2012-148

CMS-EXO-12-059

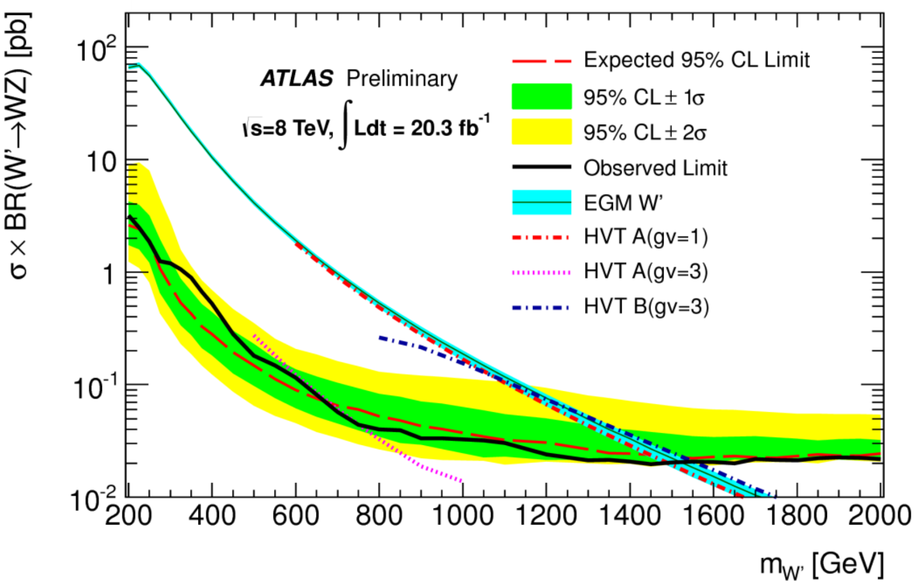


Search for a WZ resonance in all lepton final states

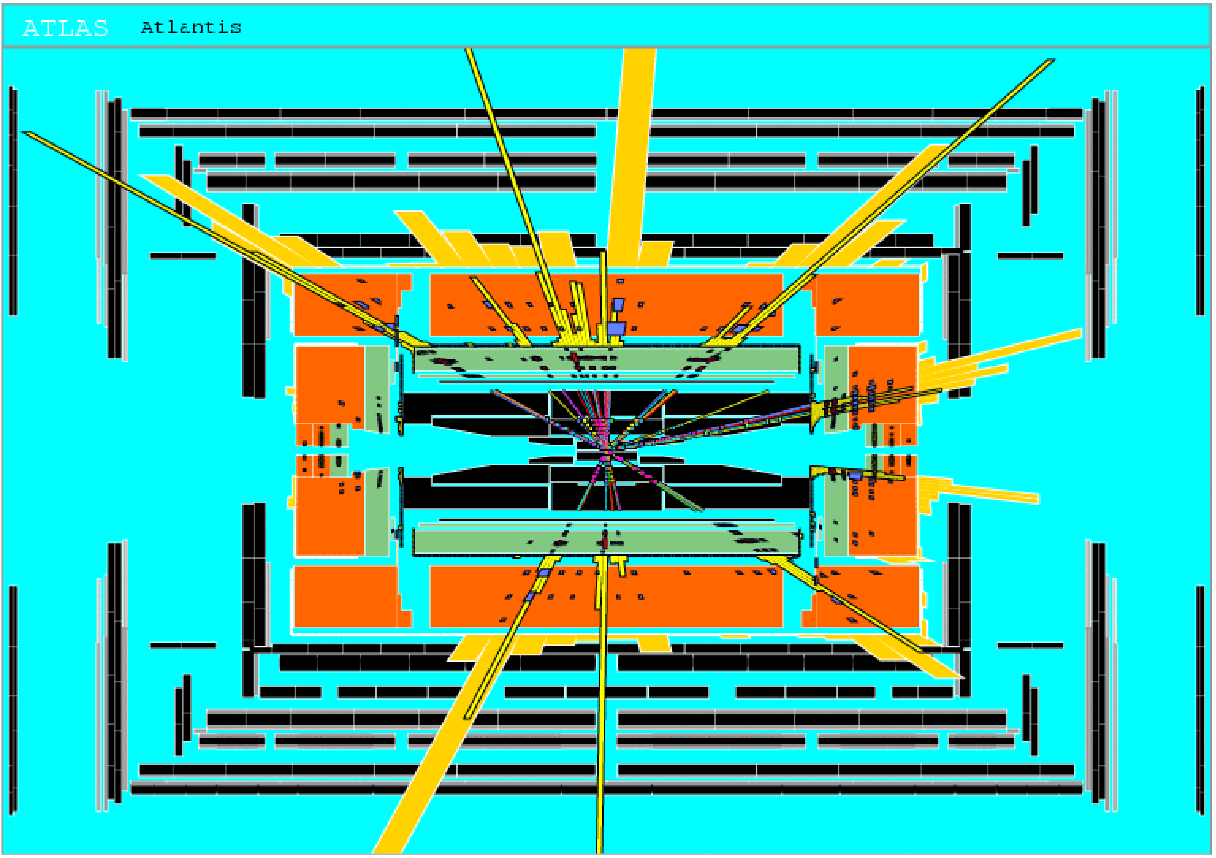
Example: W' → WZ



ATLAS-CONF-2014-015



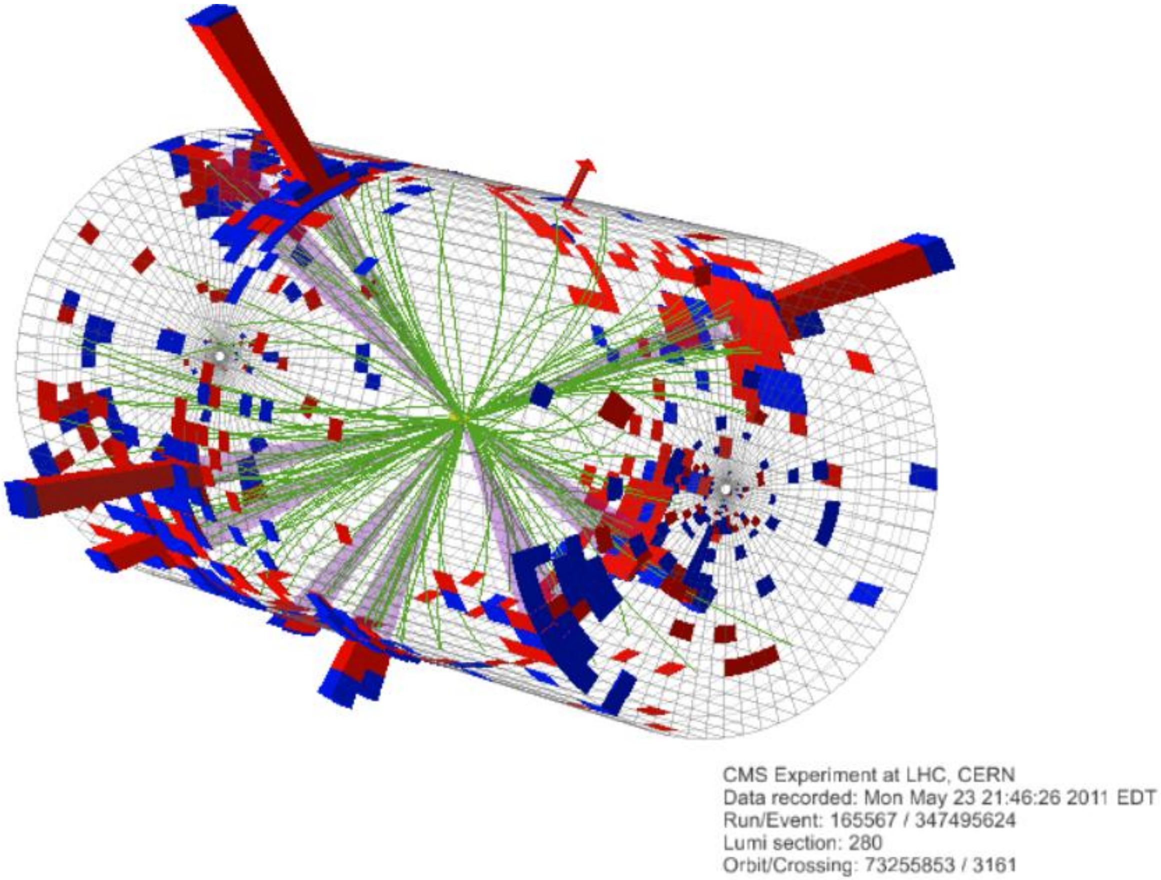
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

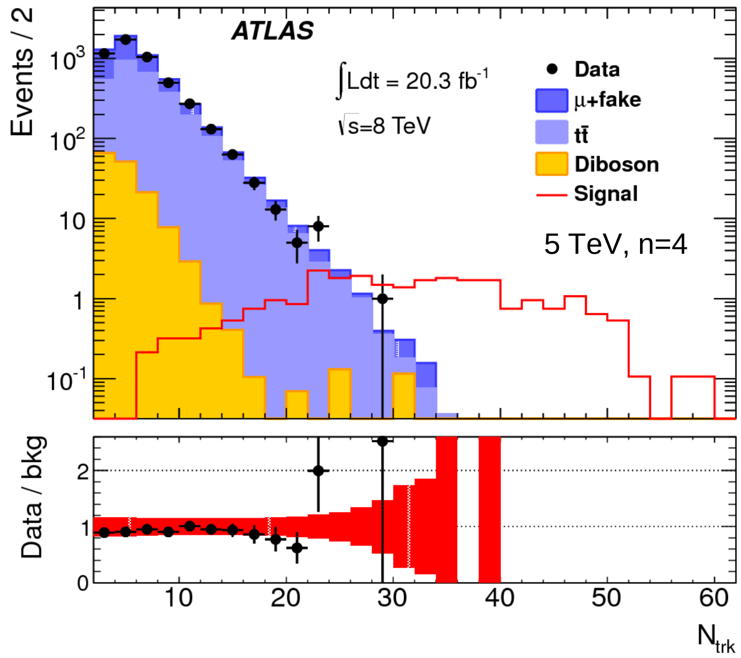
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

Search for Microscopic Black Hole production in models wth large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)



Decay into many objects (jets, leptons, photons)

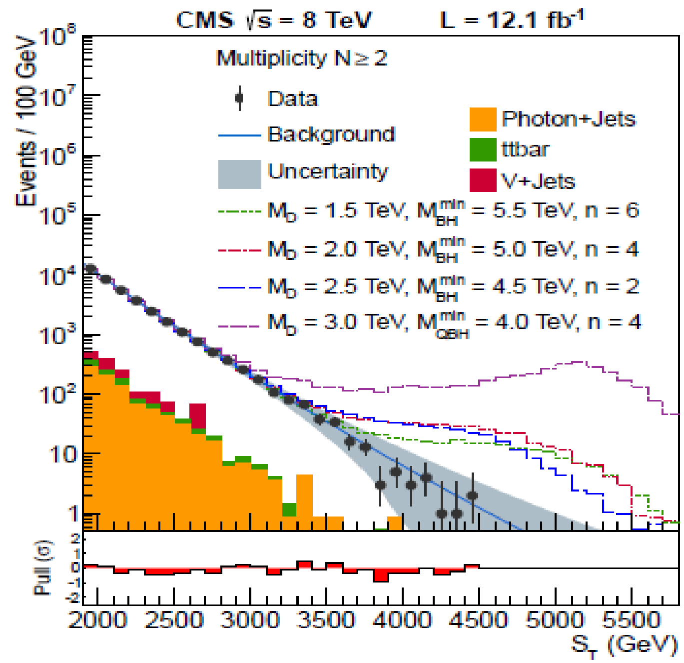
Phys Rev D88 (2013) 072001

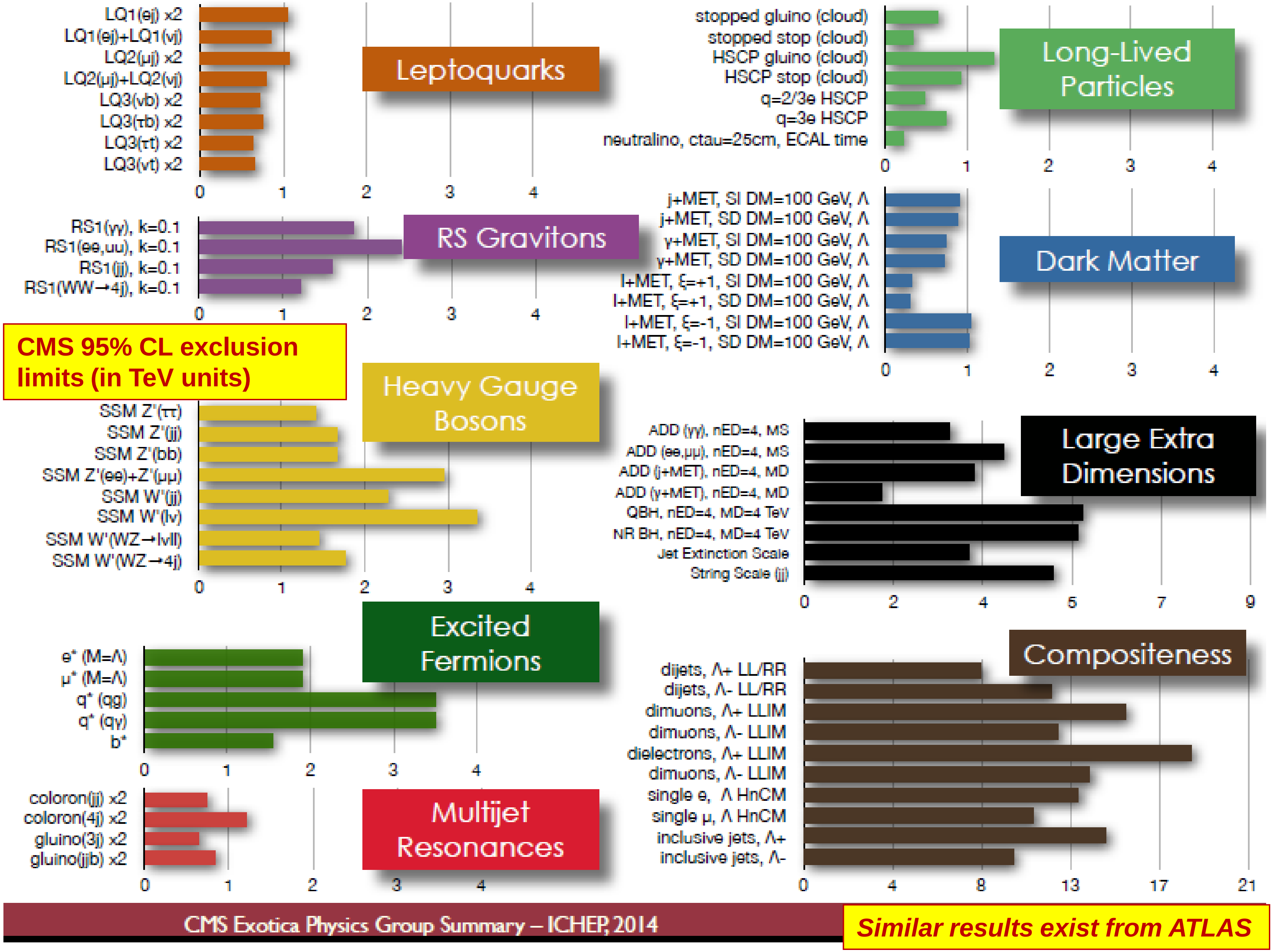
Examples: (ATLAS) two same sign muons and large multiplicity, (CMS) any three objects

($S_T = \Sigma P_T$: scalar sum of the E_T of the N objects in the event)

No deviation is seen for events with at least 3 objects with > 50 GeV pT

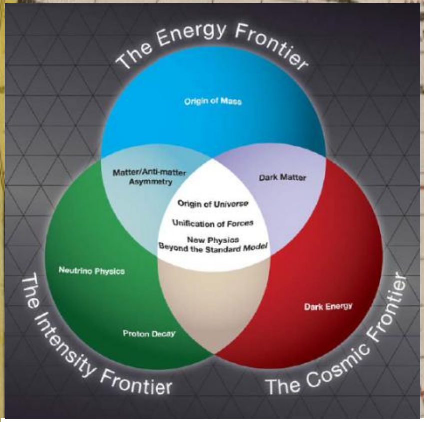
JHEP 07 (2013) 178





CMS 95% CL exclusion limits (in TeV units)
Similar results exist from ATLAS
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
CMS Exotica Physics Group Summary – ICHEP, 2014

The journey into new physics territory at the high-energy frontier has only just begun with the LHC, nevertheless…



… we need to make timely plans and courageous decisions on a global scale in order to 'plant the right seeds for the future', also beyond LHC

Thank you for your attention

J Blaeu 1664

Further reading:

The Higgs Boson

ARTICLE

Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

M. Della Negra,[1] P. Jenni,[2] T. S. Virdee[1]*

The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

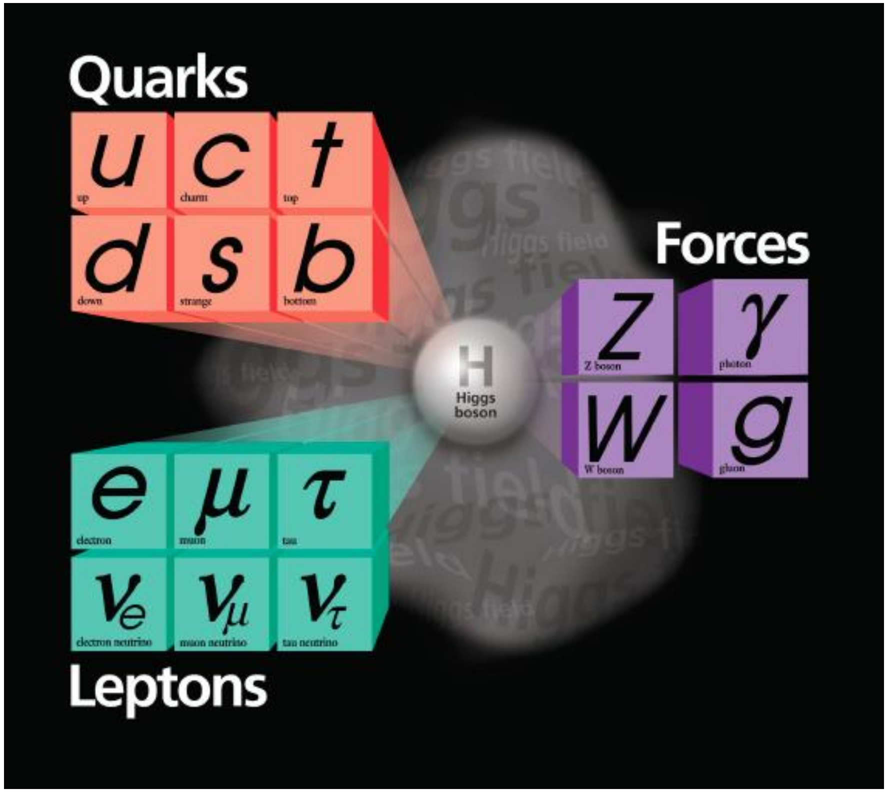
Science
AAAS

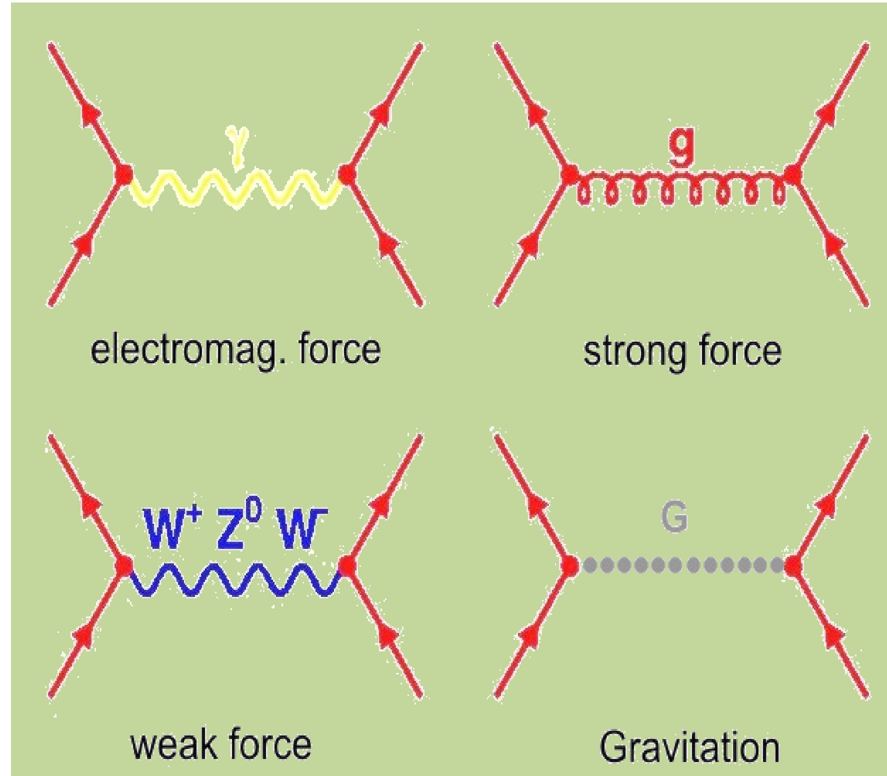
Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider
M. Della Negra *et al.*
Science **338**, 1560 (2012);
DOI: 10.1126/science.1230827

http://www.sciencemag.org/content/338/6114/1560.full.html

Spares

The Standard Model of Particle Physics



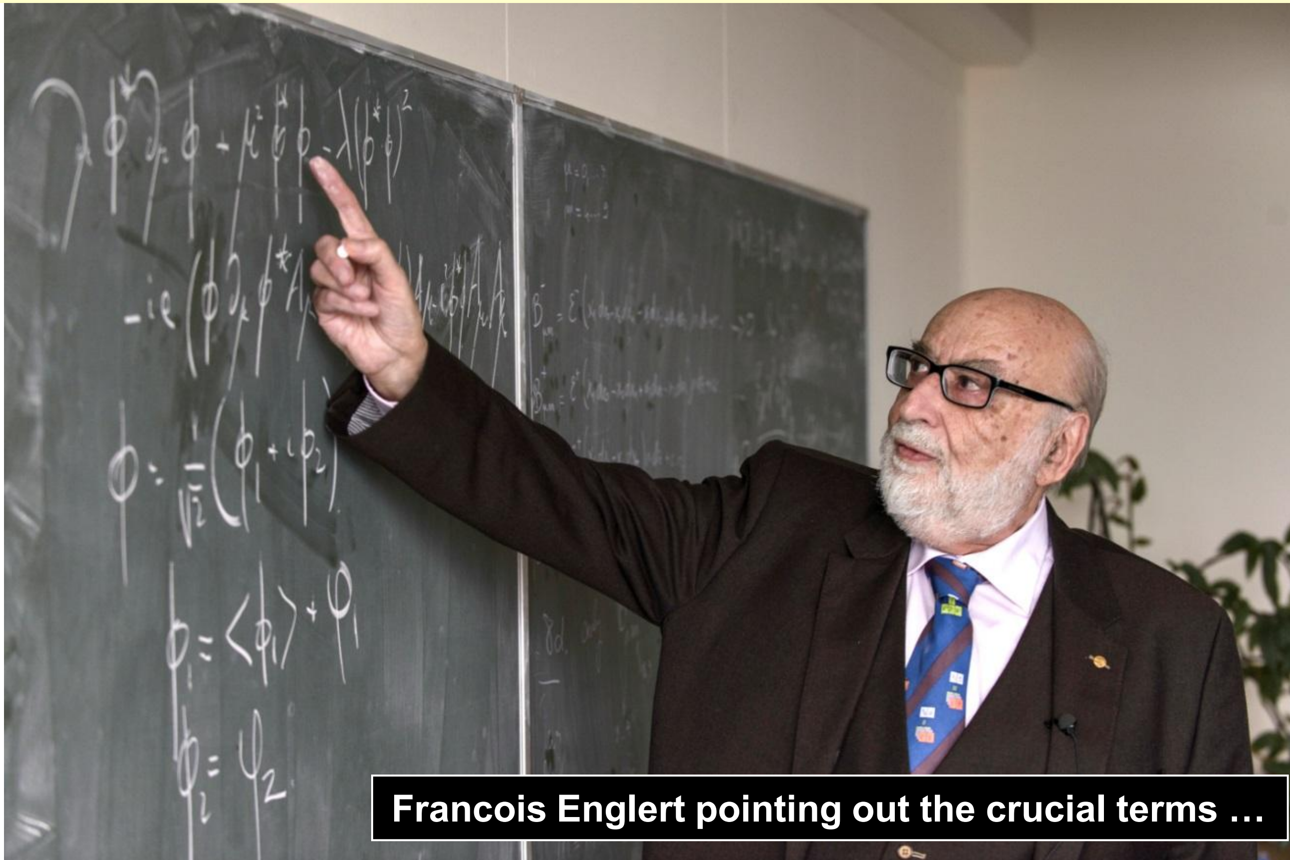


(i) Constituents of matter: quarks and leptons

(ii) Four fundamental forces
(described by quantum field theories, except gravitation)

(iii) The Brout-Englert-Higgs field (problem of mass)

Lagrangian of the Standard Model (SM)…


Francois Englert pointing out the crucial terms …

s)
d *Edition*,
ambridge, 2007,
bl.gov, 25 Aug 2013.

2) and SU(3) gauge terms)

amical term)

uon, tauon mass term)

nass term)

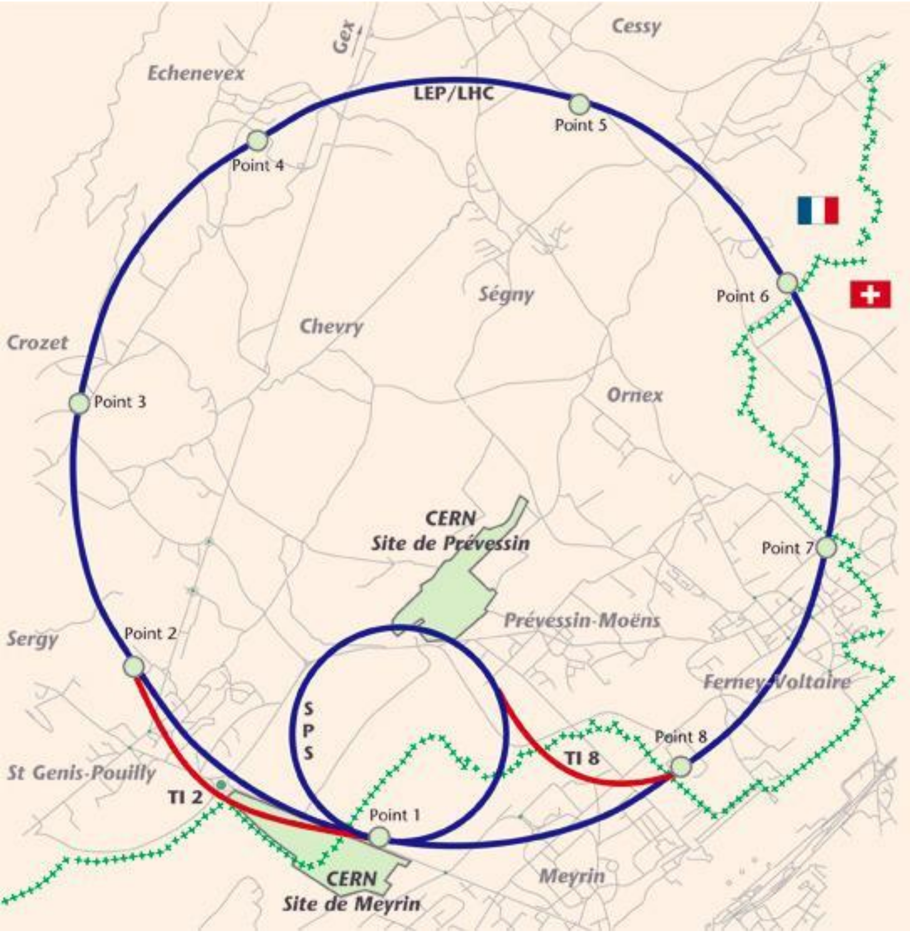
amical term)

nge, bottom mass term)

$$-\frac{\sqrt{2}}{v}\left[(-d_L,\bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R M^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right]$$ (up, charmed, top mass term)

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$ (Higgs dynamical and mass term) (1)

LHC


Cessy
Gex
Echenevex
LEP/LHC
Point 5
Point 4
Ségny
Point 6
Chevry
Crozet
Ornex
Point 3
CERN
Site de Prévessin
Point 7
Prévessin-Moëns
Sergy
Point 2
Ferney-Voltaire
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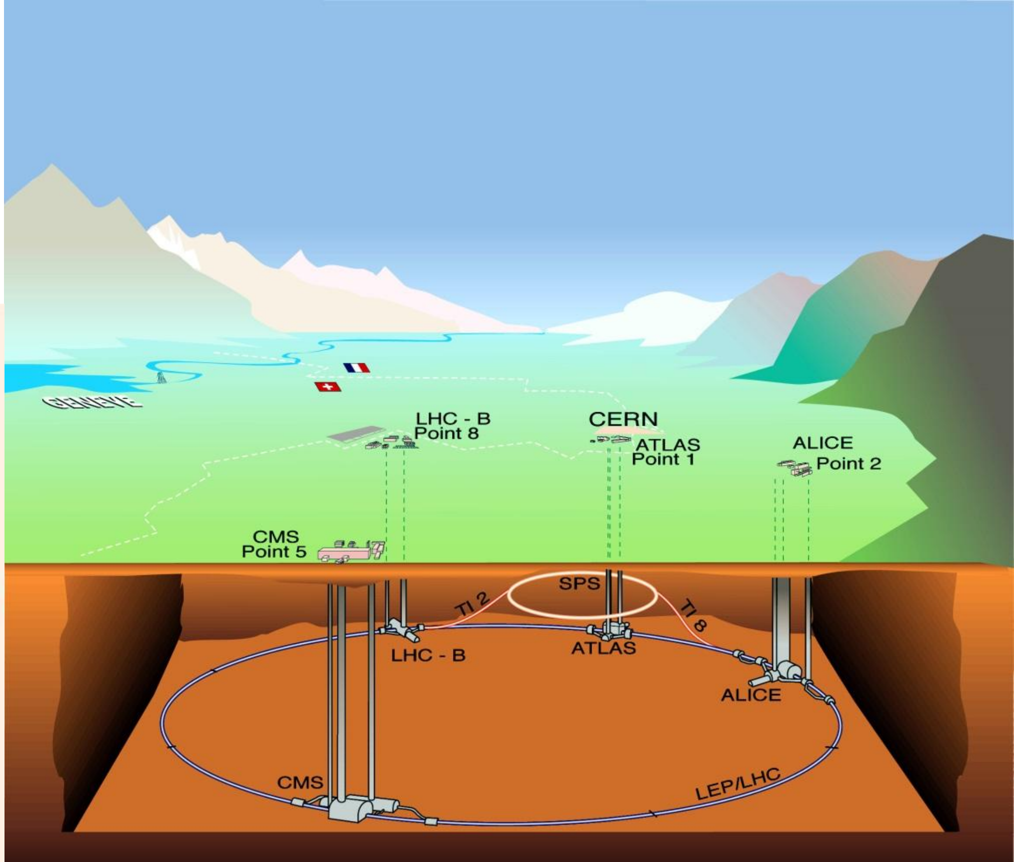
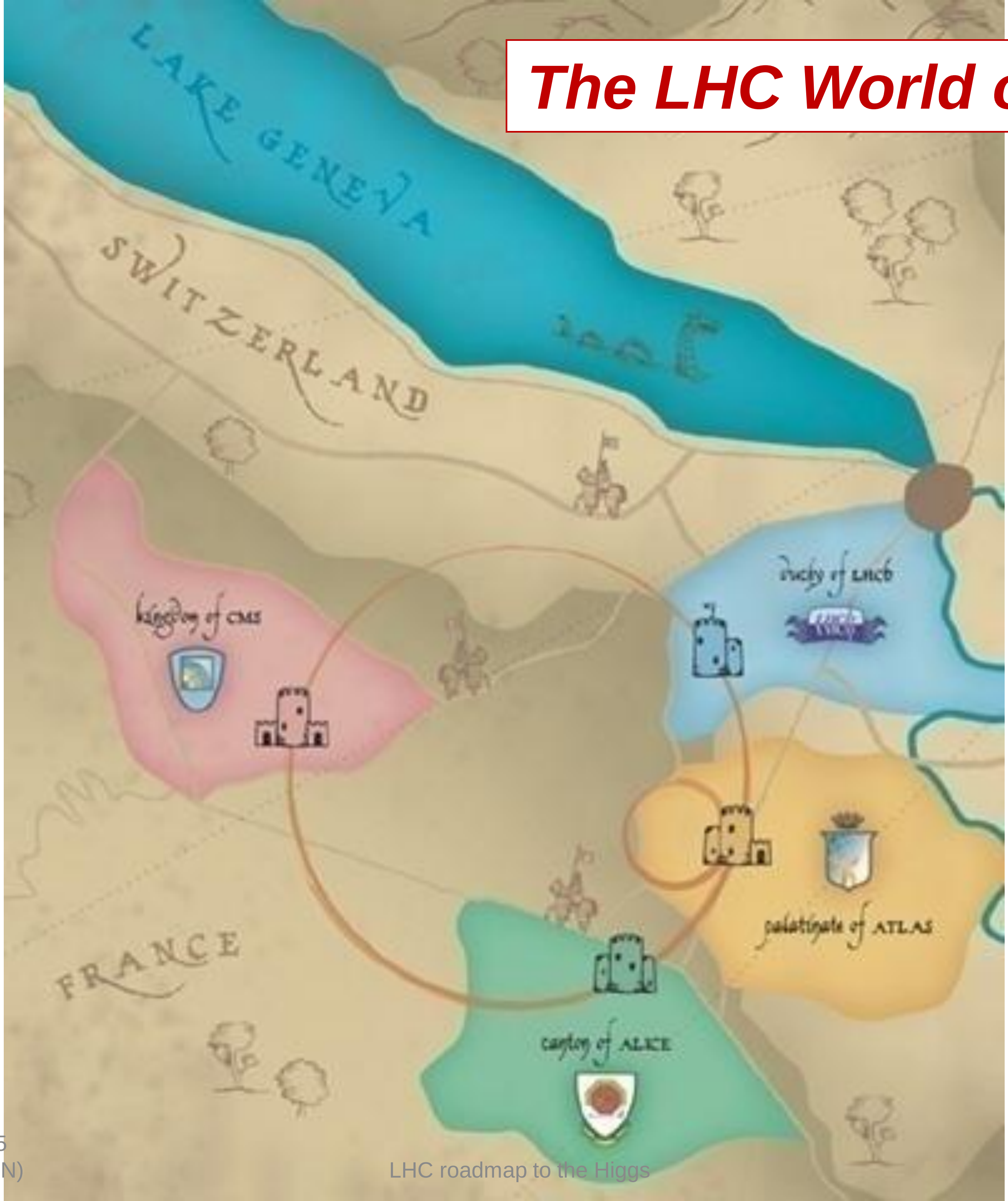
S
Point 8
TI 8
St Genis-Pouilly
TI 2
Point 1
CERN
Site de Meyrin
Meyrin


GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 2
TI 8
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

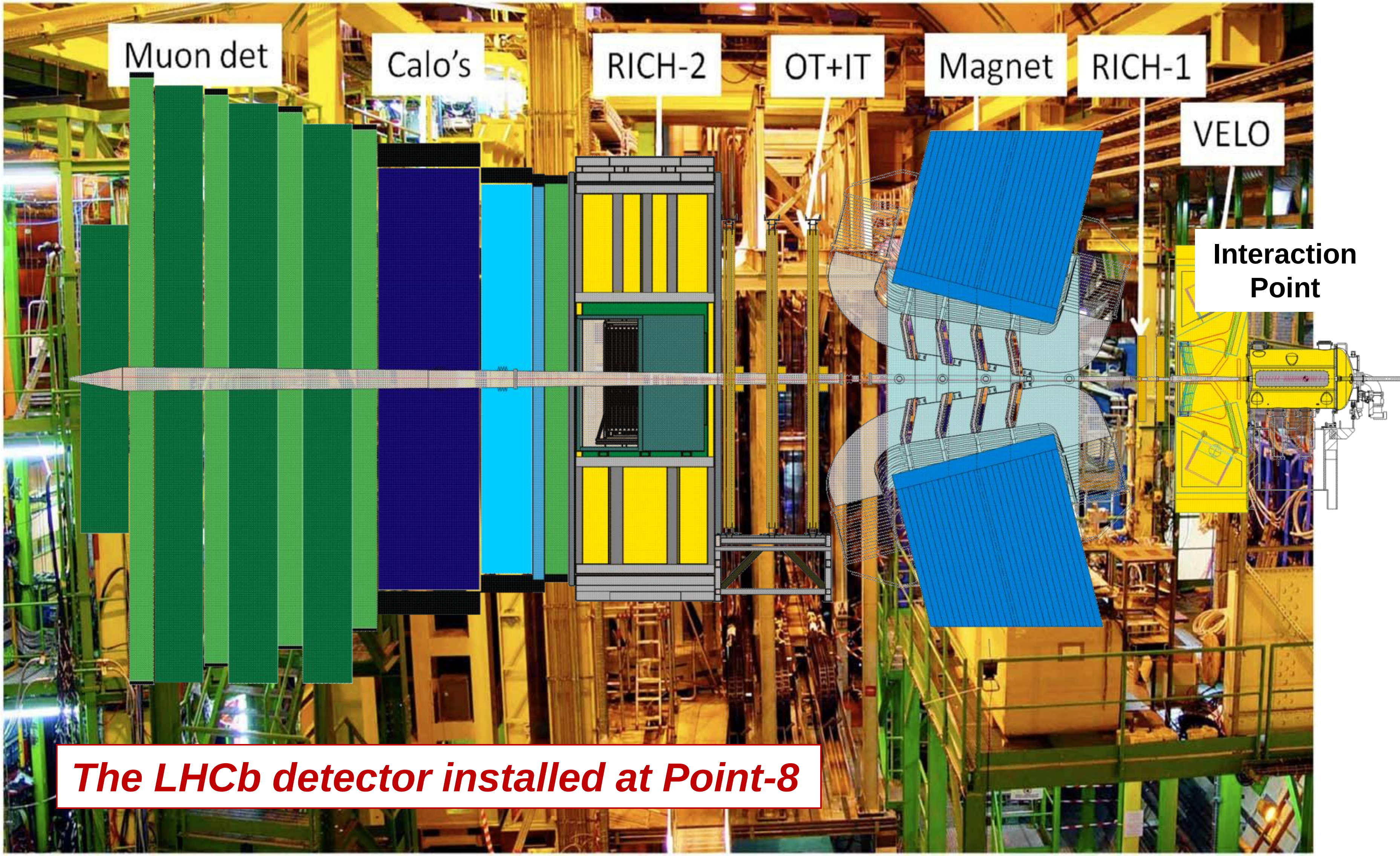


CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
178 Institutions
38 countries
550 MCHF

ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF



The LHCb detector installed at Point-8

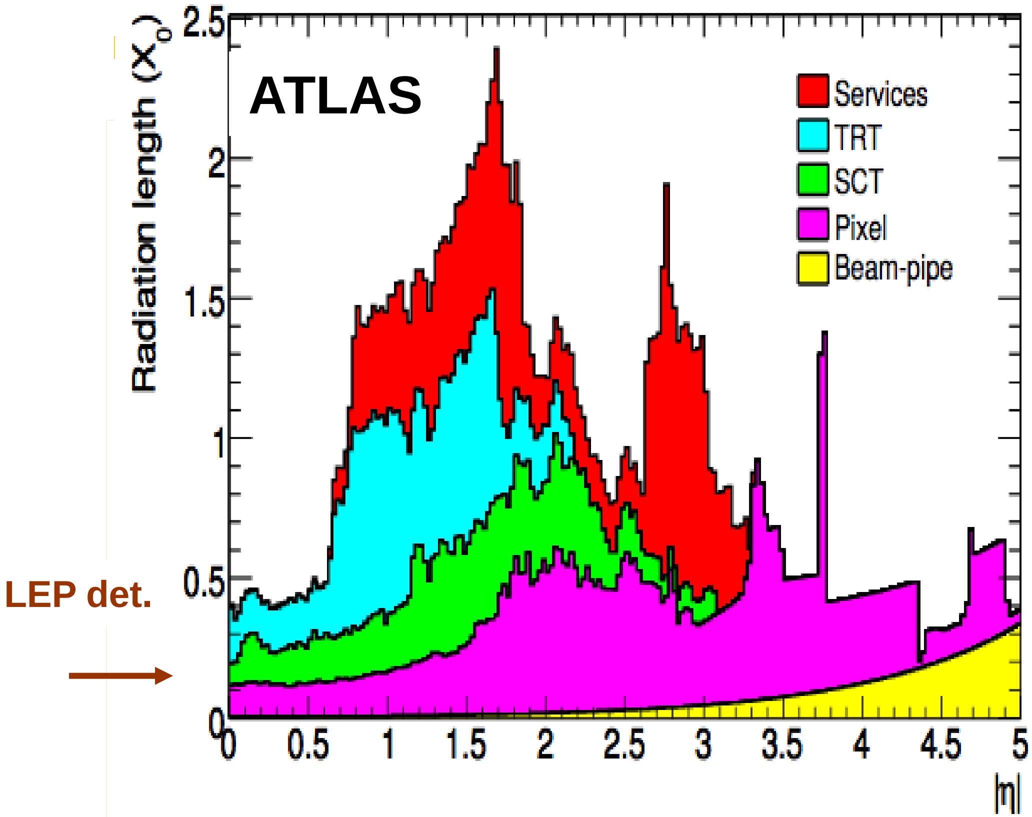
Charged Particle Interactions with Matter

Particles are detected through their interaction with the active detector materials

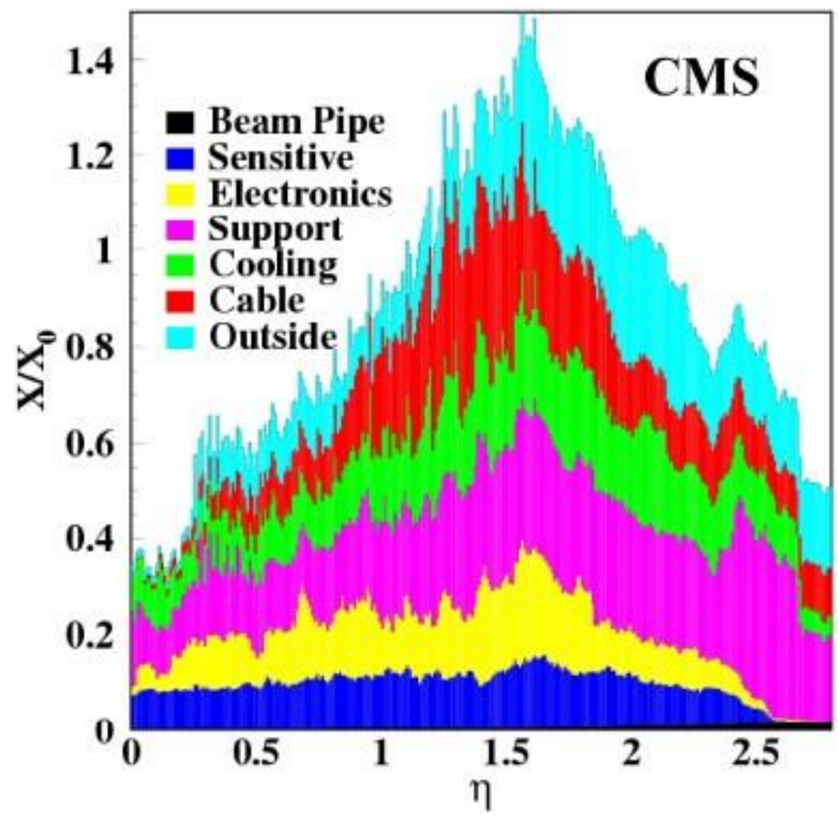
Inner tracker material through planning and construction

- Energy loss by ionisation
- Bremsstrahlung
- Multiple scattering

Weight: 4.5 tons

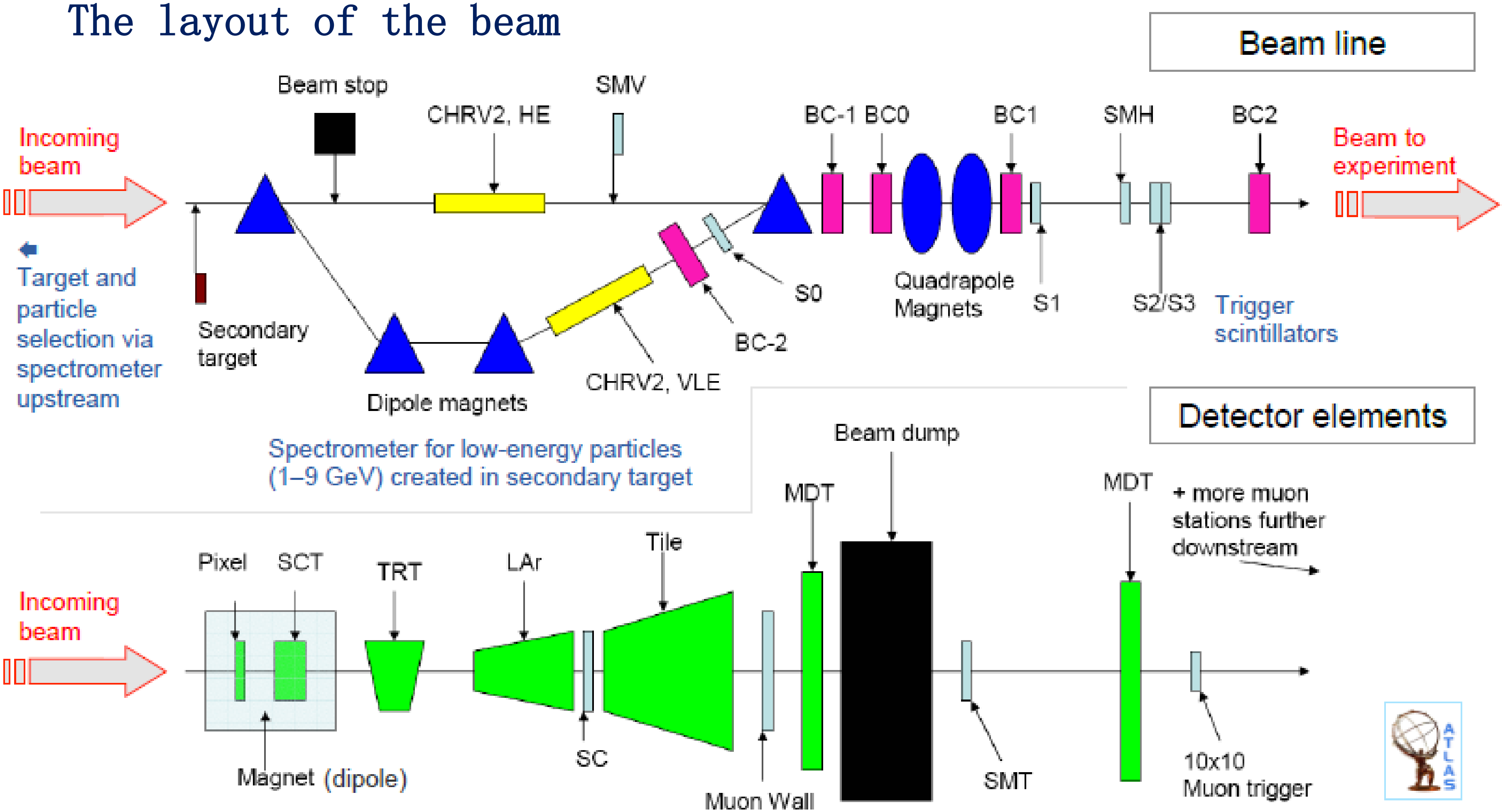


Weight: 3.7 tons



For ATLAS, need to add ~2 X_0 (η = 0) from solenoid + cryostat in front of EM calorimeter

The layout of the beam



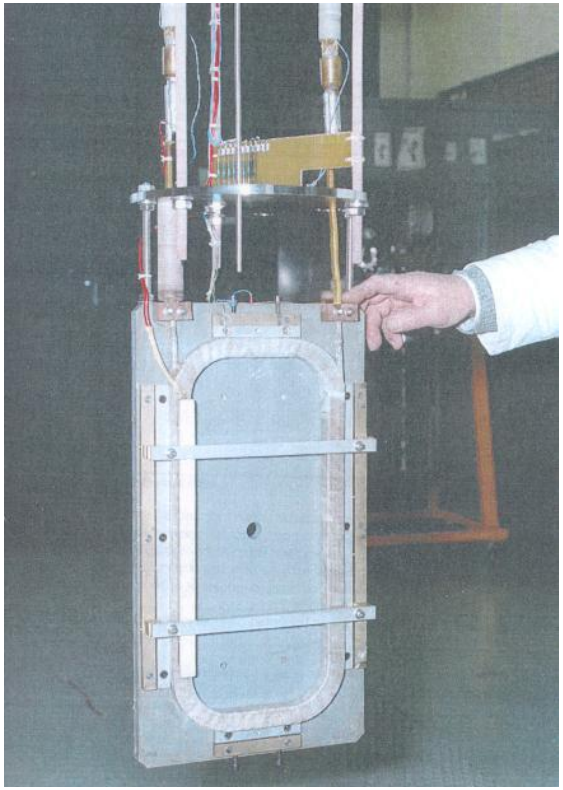
~ 90 million events collected

$e^{\pm}$, $\pi^{\pm}$	$1 \rightarrow 250$ GeV
$\mu^{\pm}$, $\pi^{\pm}$, p	up to 350 GeV
γ	20–100 GeV

B-field = $0 \rightarrow 1.4$ T

Many configurations
(e.g. additional material in ID,
25 ns runs, …)

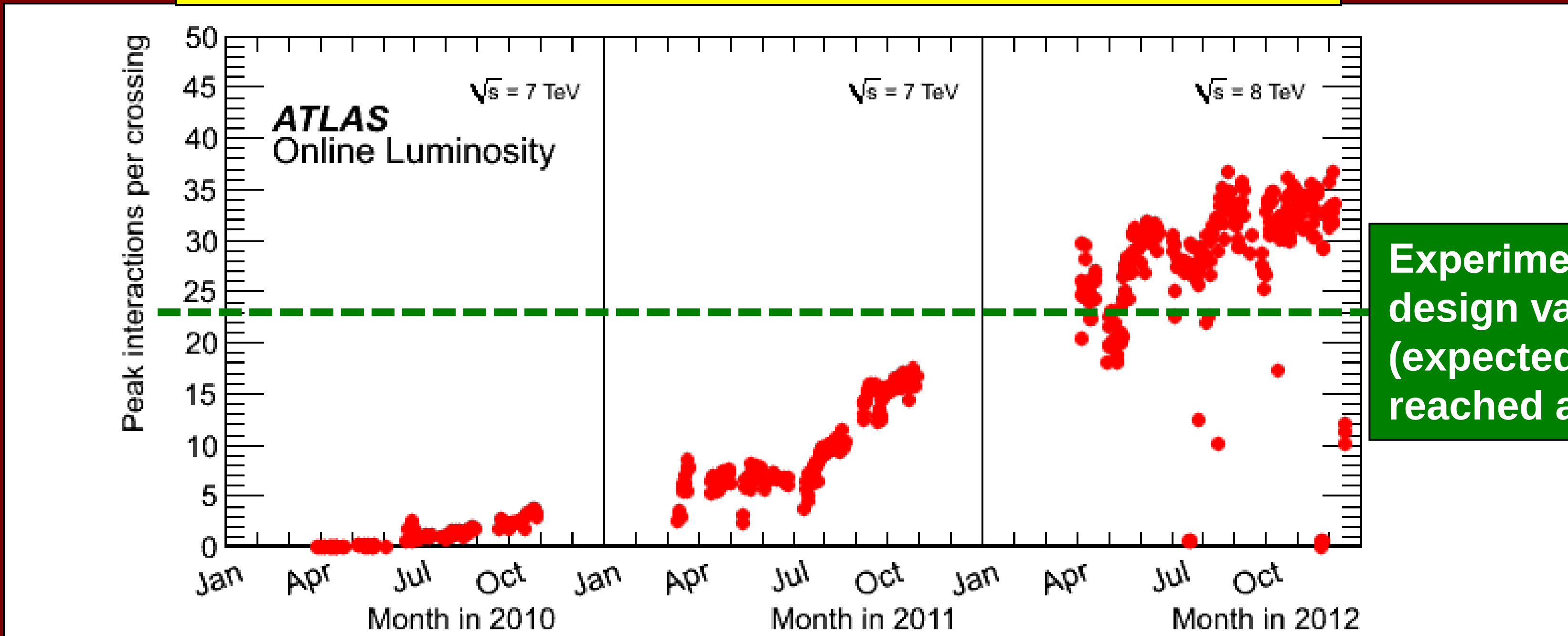
From small to big:
Important first steps towards the ATLAS Barrel Toroid



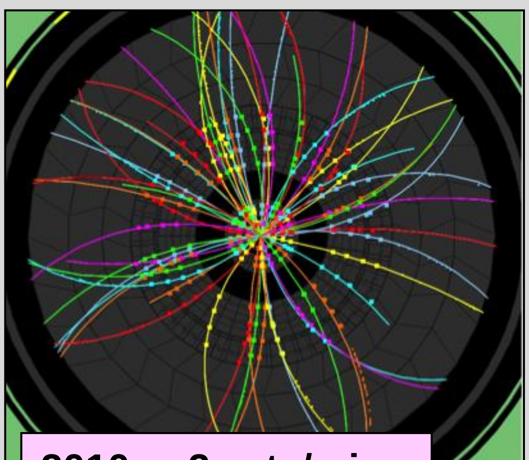
Micro-B coil (Saclay R&D)

The ATLAS Race-Track coil at Saclay

The prize to pay for the high luminosity: pile-up
(number of simultaneous pp interactions per bunch crossing)



Experiment's design value (expected to be reached at L=10^{34} !)



2010: ~ 2 evts/x-ing

2011: ~ 10 evts/x-ing

2012: ~ 20 evts/x-ing

The optical theorem can be used together with the luminosity to determine the total cross section :

$$\sigma_{tot} \propto 4\pi \cdot \mathrm{Im}\left(f_{el}\right)_{t\to 0}$$

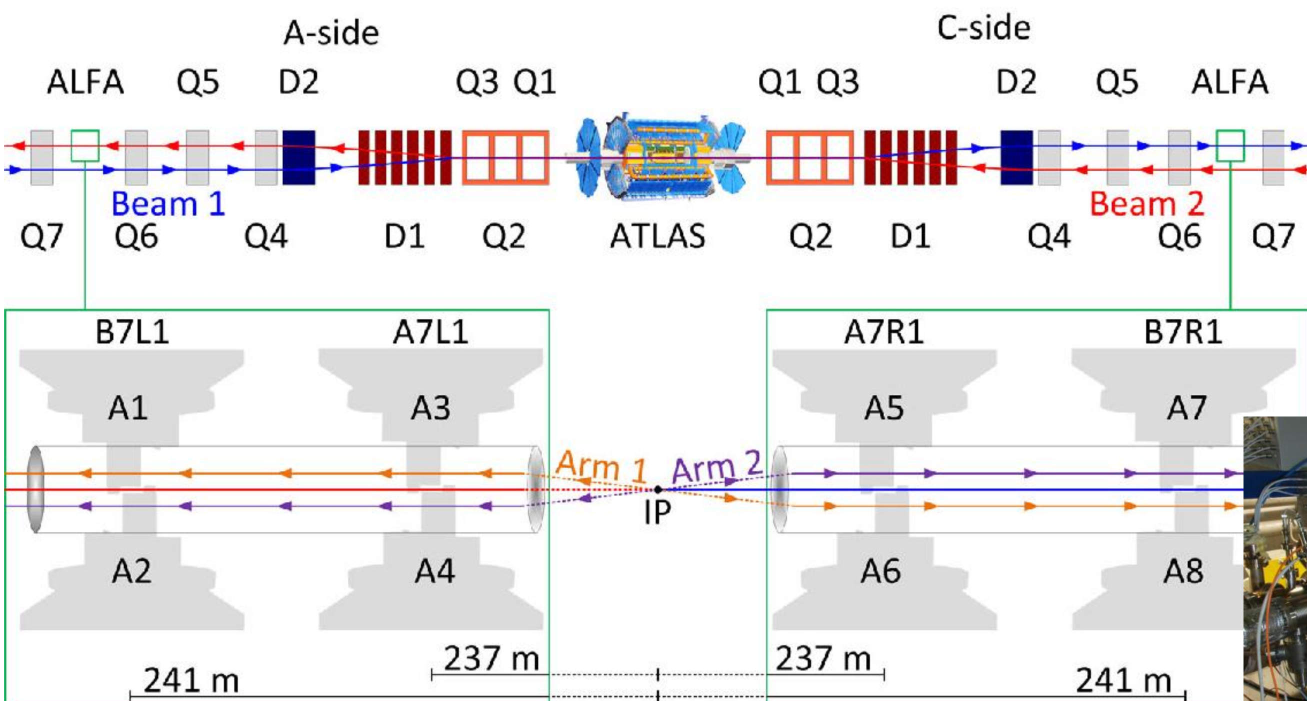
$$\sigma_{tot}^{2} = \frac{1}{L} \cdot \frac{16\pi}{1+\rho^{2}} \cdot \left.\frac{dN_{el}}{dt}\right|_{t\to 0}$$

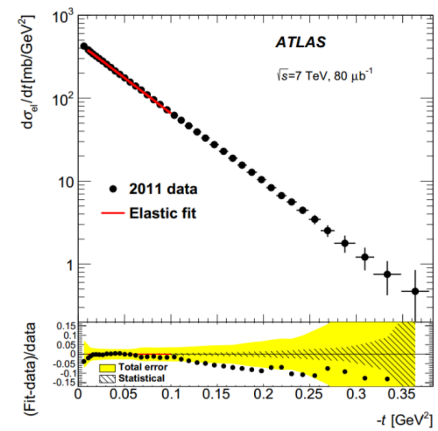
$$\rho = \left.\frac{\mathrm{Re}\left(f_{el}(t)\right)}{\mathrm{Im}\left(f_{el}(t)\right)}\right|_{t\to 0}$$

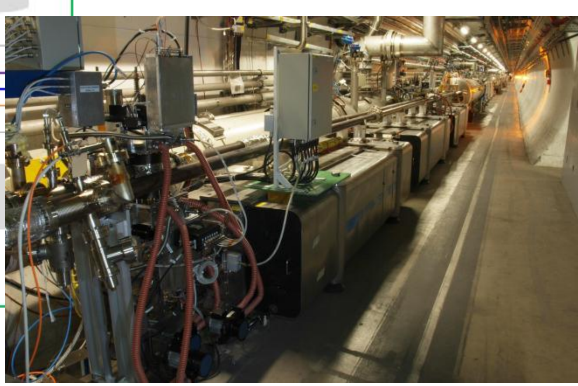
Luminosity-dependent method
ρ taken from model extrapolation

Requires measurement of differential elastic cross section in t:

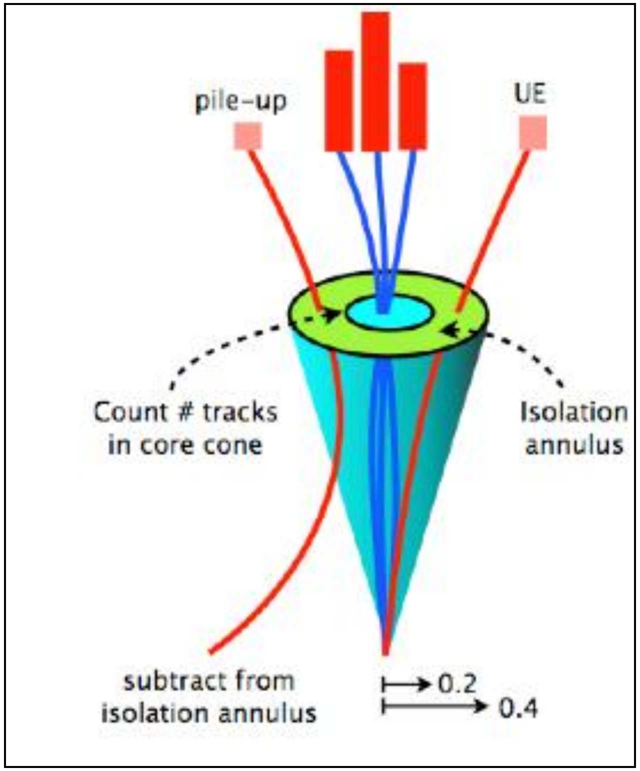
$$t = -\left(p\theta^{*}\right)^{2}$$



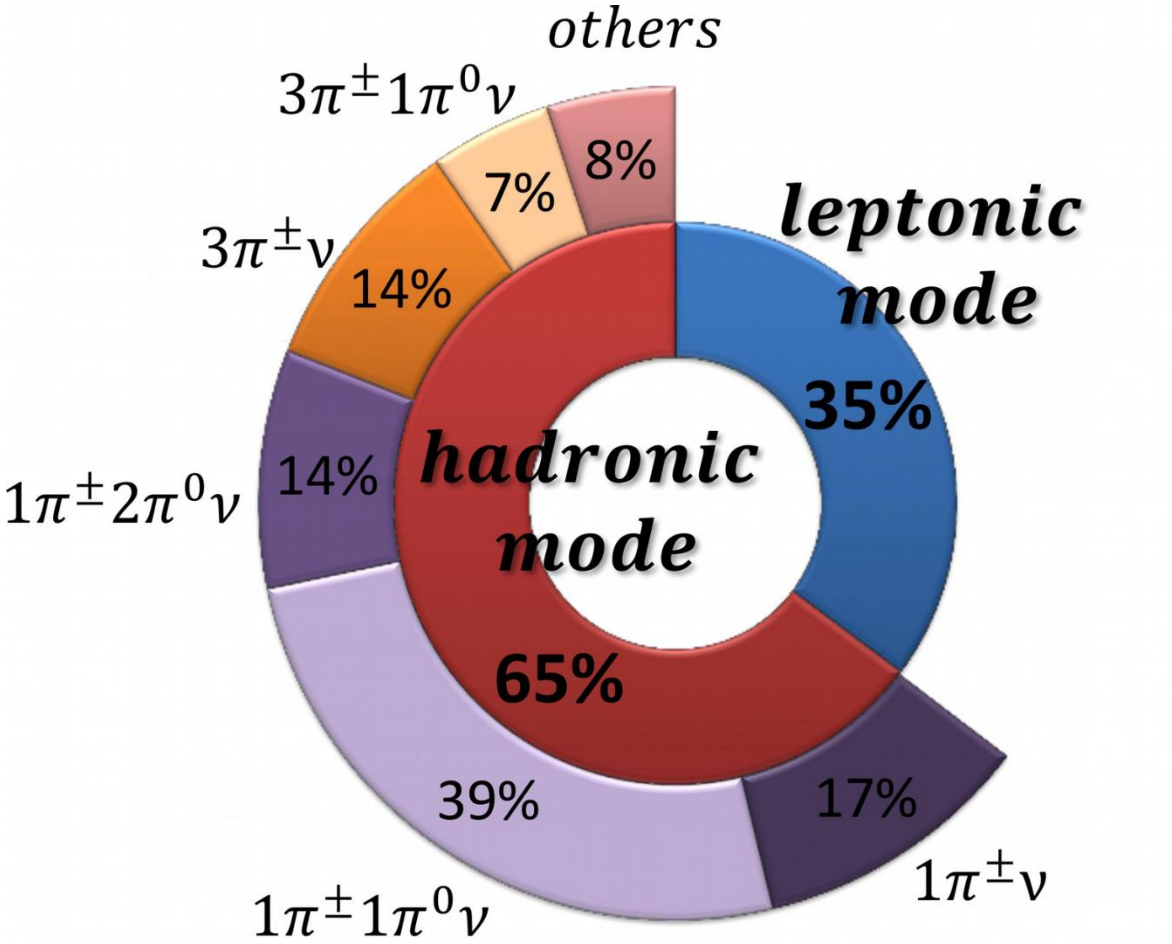




τ

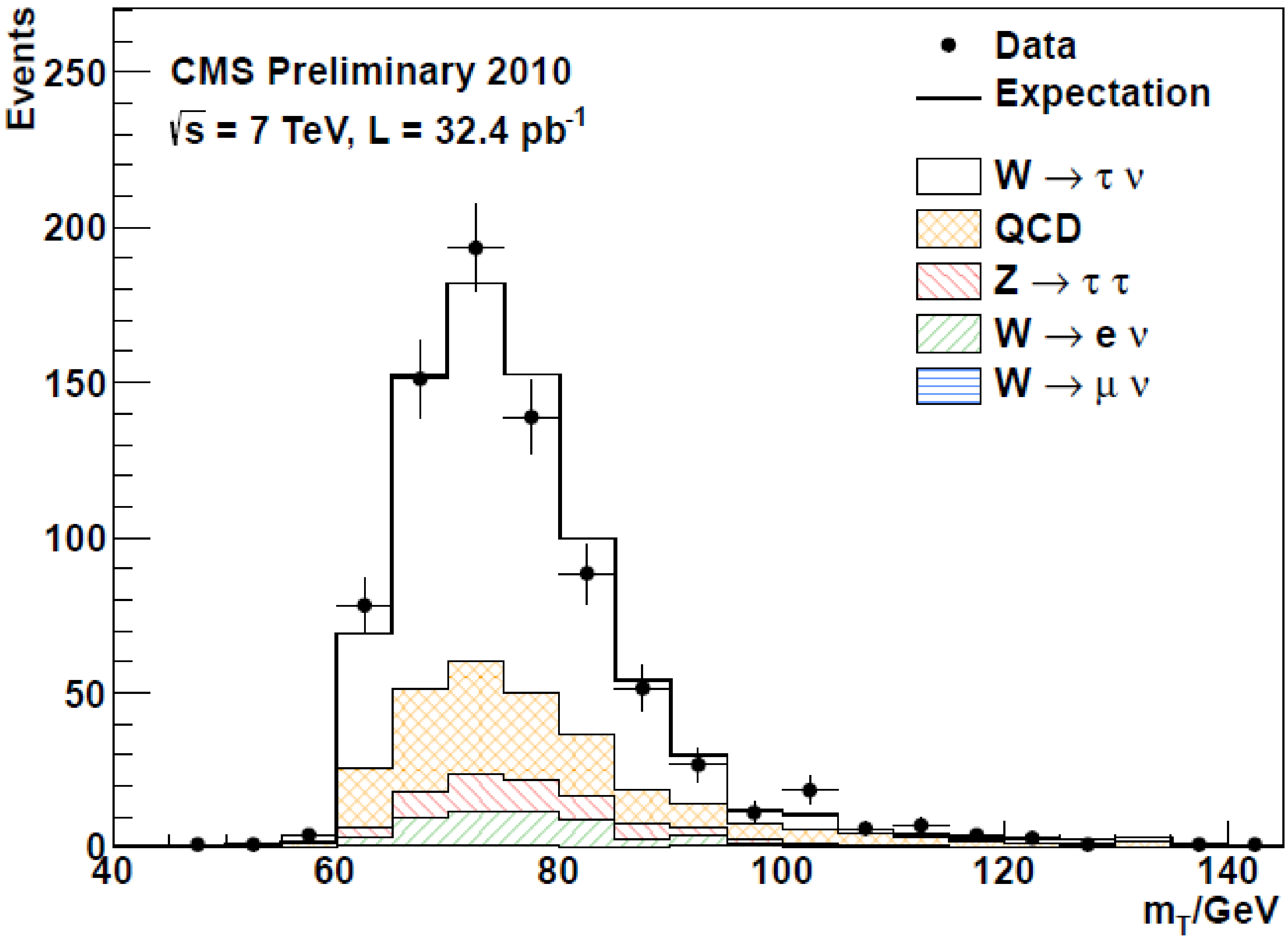


pile-up
UE
Count # tracks
in core cone
Isolation
annulus
subtract from
isolation annulus
0.2
0.4



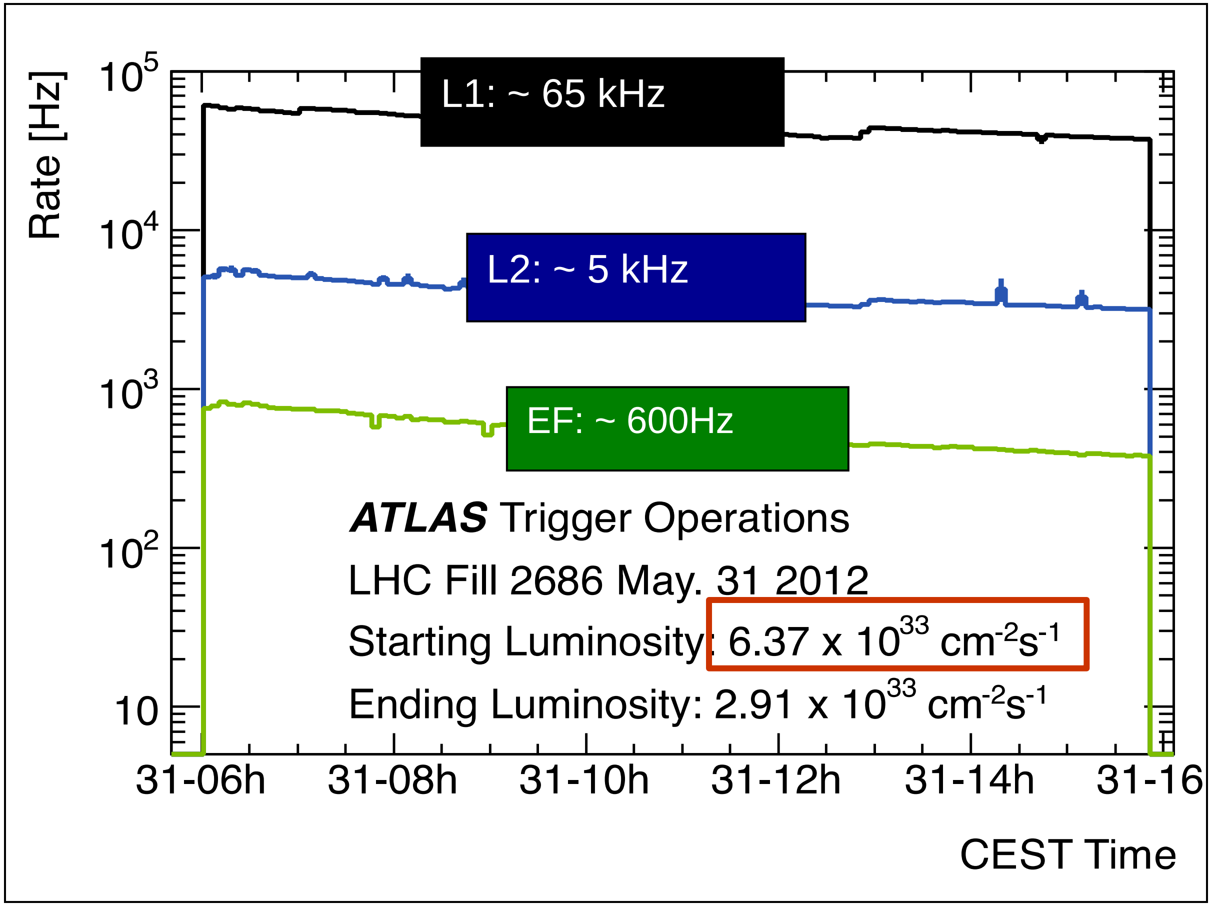
others
$3\pi^{\pm}1\pi^{0}\nu$
8%
7%
$3\pi^{\pm}\nu$
14%
leptonic
mode
35%
hadronic
mode
$1\pi^{\pm}2\pi^{0}\nu$
14%
65%
39%
17%
$1\pi^{\pm}\nu$
$1\pi^{\pm}1\pi^{0}\nu$

W → τν signal



CMS-PAS-EWK-11-019

Example for the typical trigger rates



Three levels of event selections:

Level-1 underground with purpose-made electronics and processors

Level-2 and Event Filter in a large computer farm located at the surface of Point-1

(Noted in the plot are the output rates)

- ❑ **Typical recorded rates for main streams e/γ, Jets/τ/E_T^{miss} , Muons: ~ 100 Hz each**
- ❑ **Delayed stream (future Tier0 reconstruction): B-physics (~65 Hz) and Hadronic (~80 Hz)**
- ❑ **Note: currently 564 items in the trigger menu**

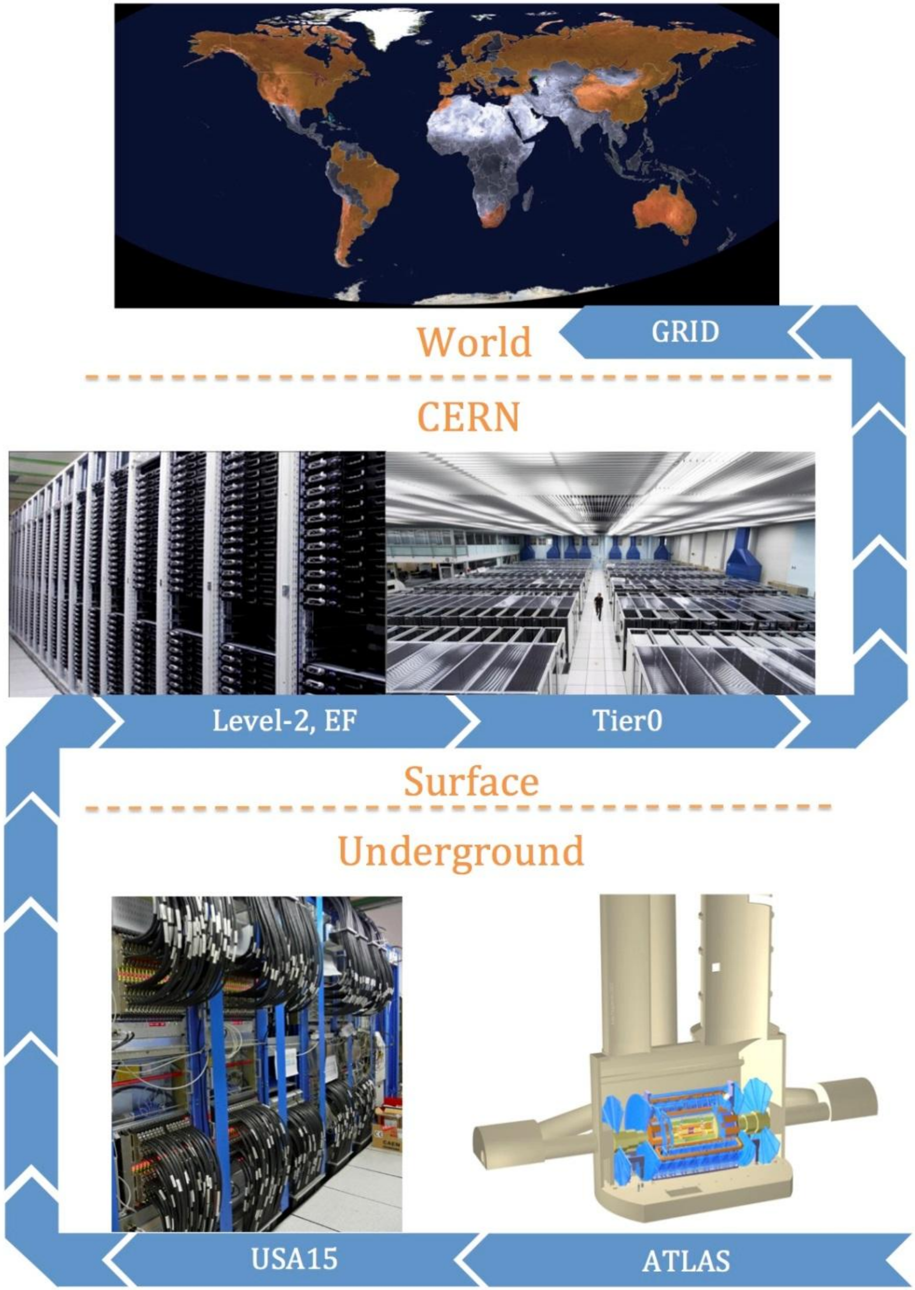
The Worldwide LHC Computing Grid (WLCG)

GRID computing developed to solve problem of data storage and analysis

LHC data volume per year: ~25 Petabytes

One CD has ~ 600 Megabytes
1 Petabyte = 10^9 MB = 10^{15} Byte
→ Stack of 30 km of CDs !

(Note: the WWW is from CERN...)

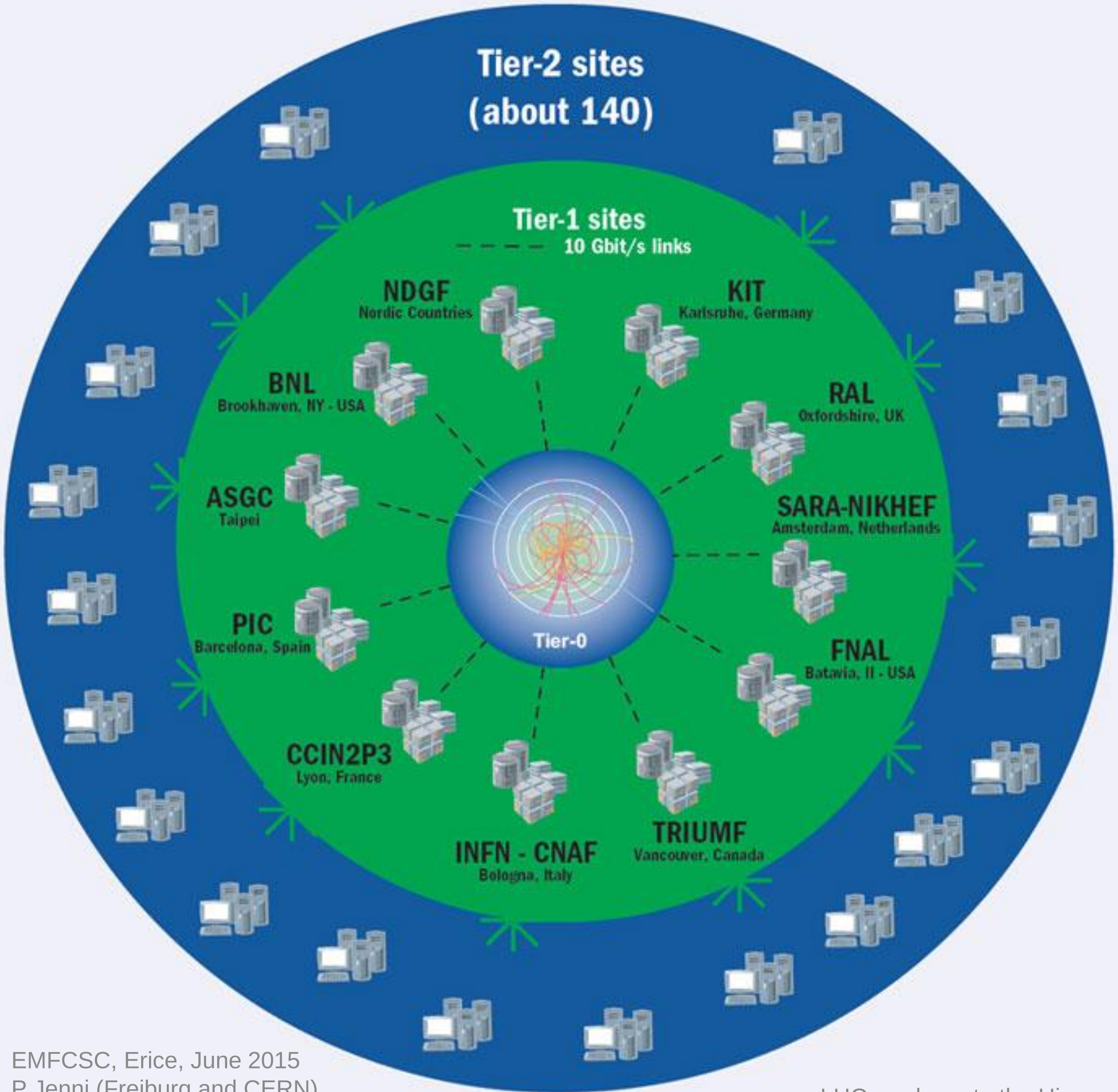


Data flow

Example: Operational channels in ATLAS at the start of Run-2 (May 2015)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	99.0%
SCT Silicon Strips	6.3 M	98.9%
TRT Transition Radiation Tracker	350 k	97.3%
LAr EM Calorimeter	170 k	100%
Tile calorimeter	4900	99.2%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	98.7%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	357 k	99.8%
CSC Cathode Strip Chambers	31 k	98.4%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	99.8%

The Worldwide LHC Computing Grid (WLCG)



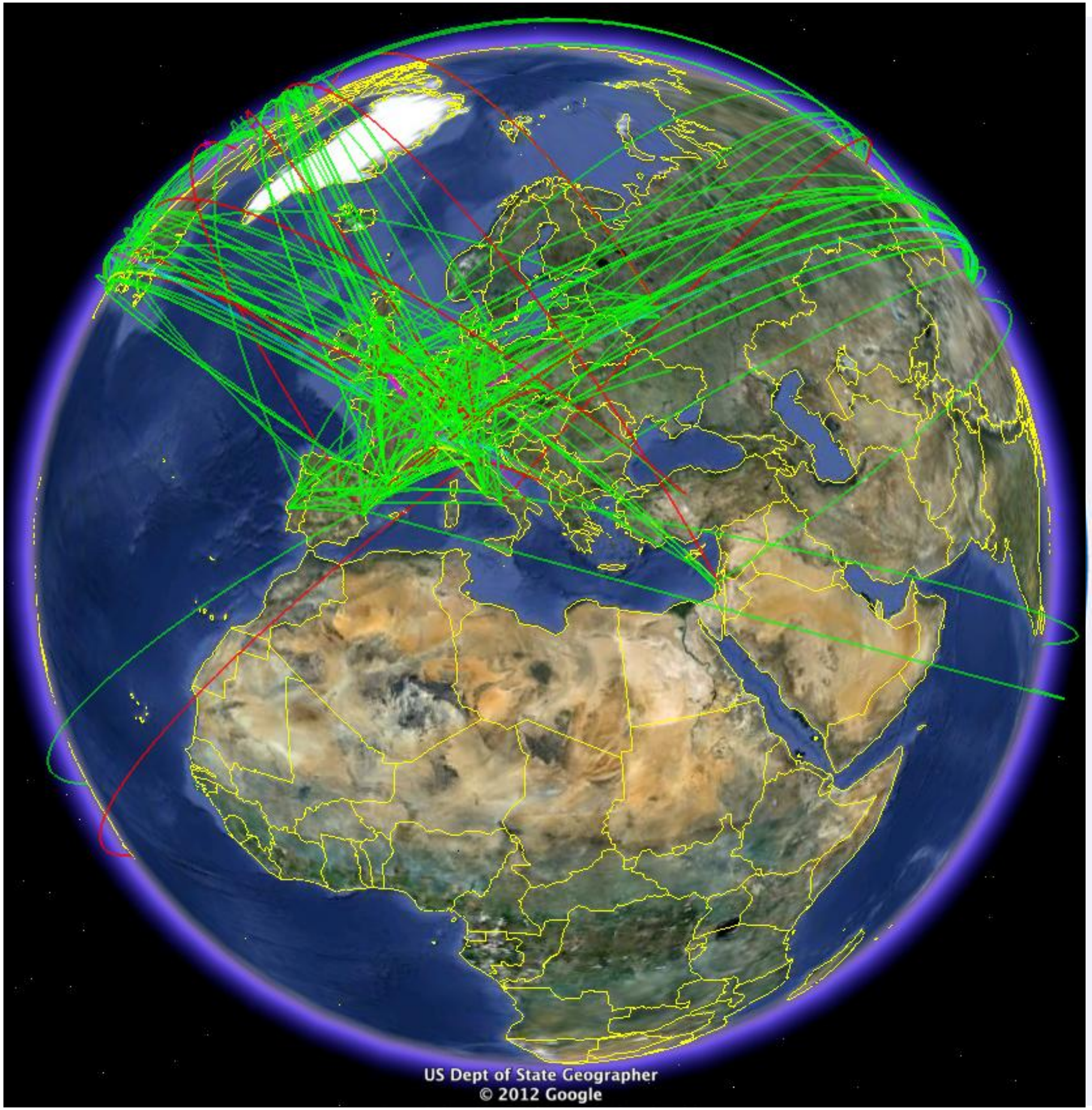
WLCG Worldwide LHC Computing Grid

Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (12 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (68 federations of >100 centres):
- Simulation
- End-user analysis

The Worldwide LHC Computing Grid (WLCG)



Tier-0 (CERN):
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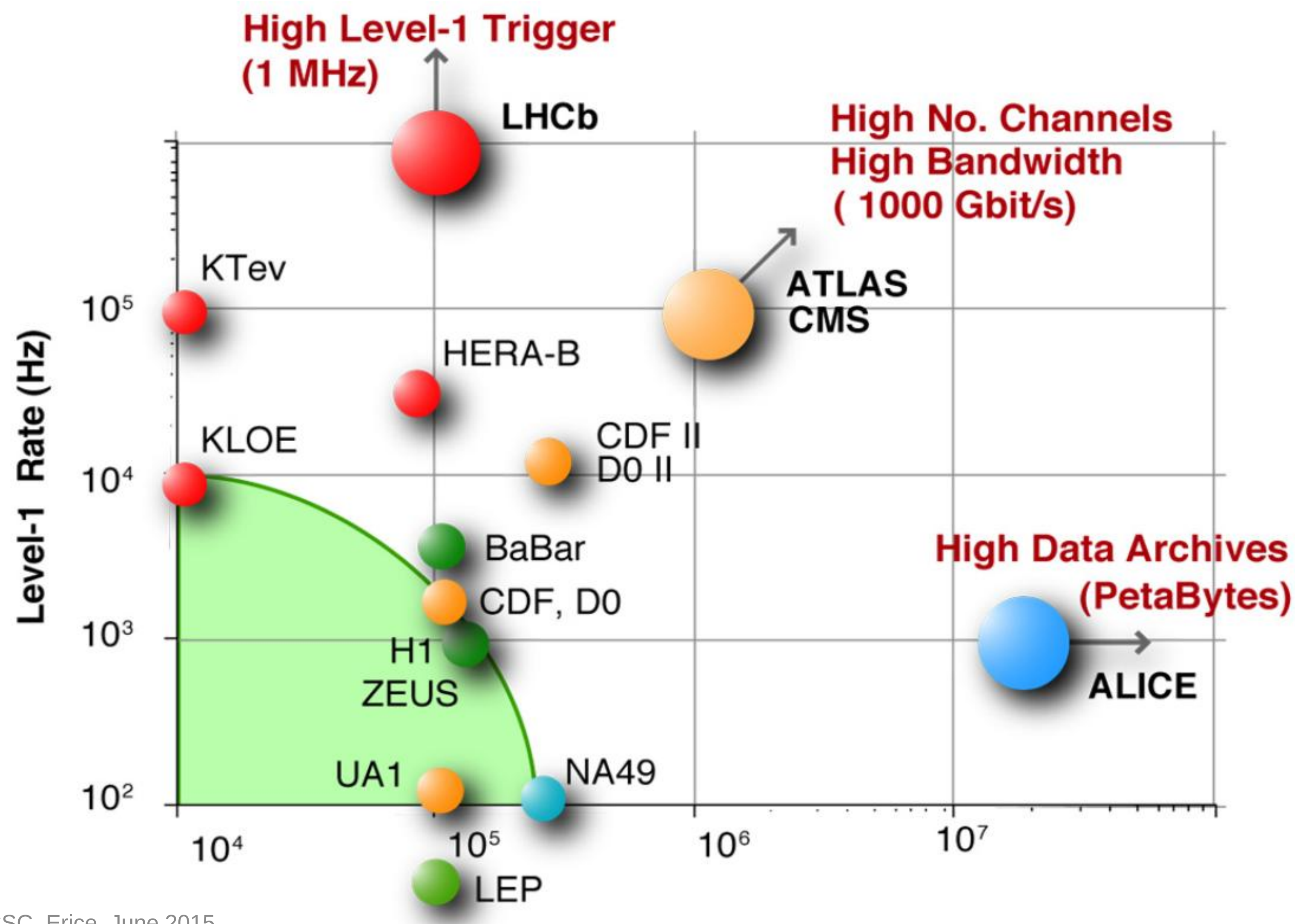
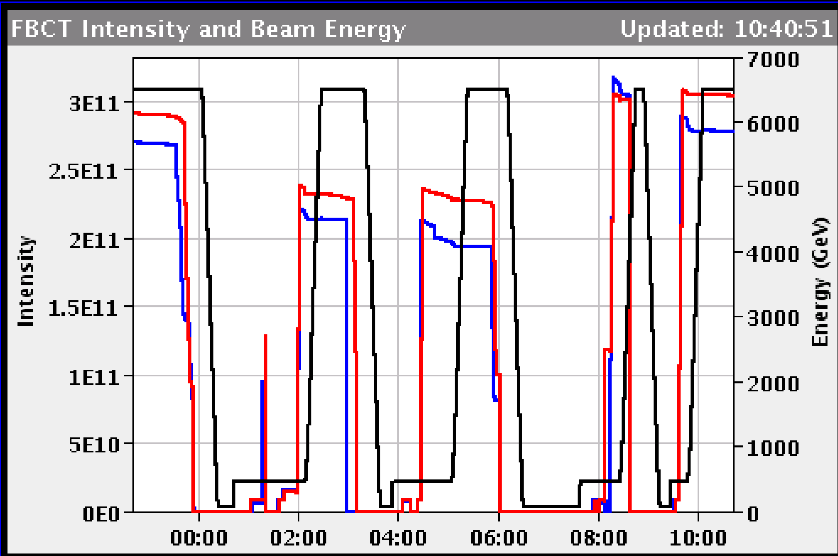
DAQ and Computing requirements at LHC

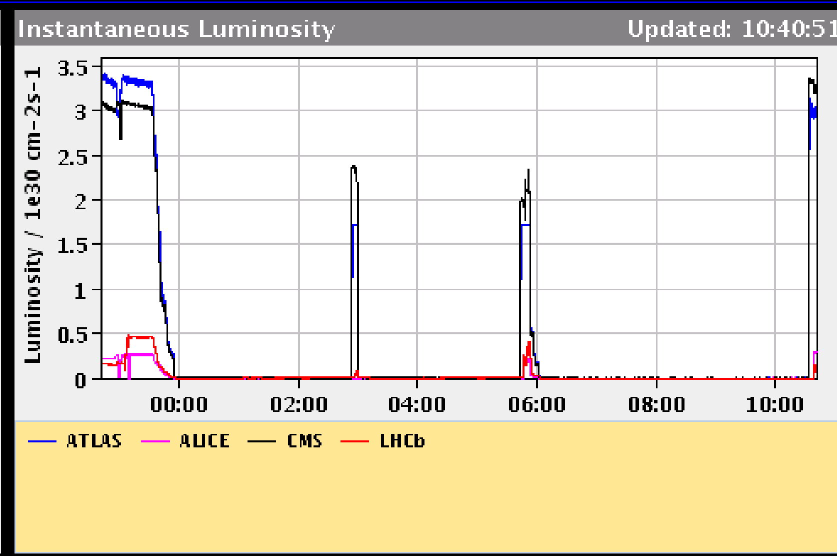


LHC Page1 | Fill: 3819 | E: 6500 GeV | t(SB): 00:00:19 | 03-06-15 10:40:51

PROTON PHYSICS: STABLE BEAMS

Energy:	6500 GeV	I(B1):	2.93e+11	I(B2):	2.96e+11



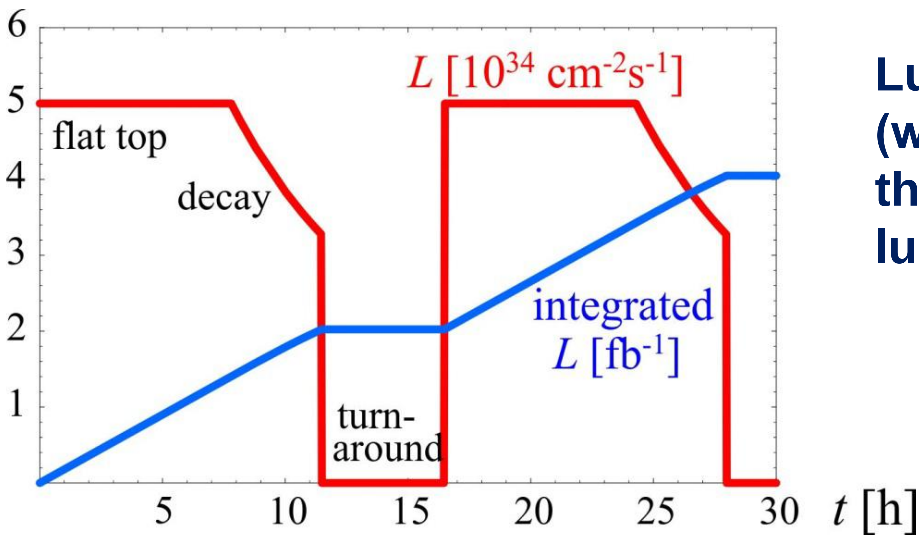


Comments (03-Jun-2015 10:40:01)

collapsed separation bumps in IP1 and 5
collapsed separation bumps in I IP2 and 8
preparing for stable beams

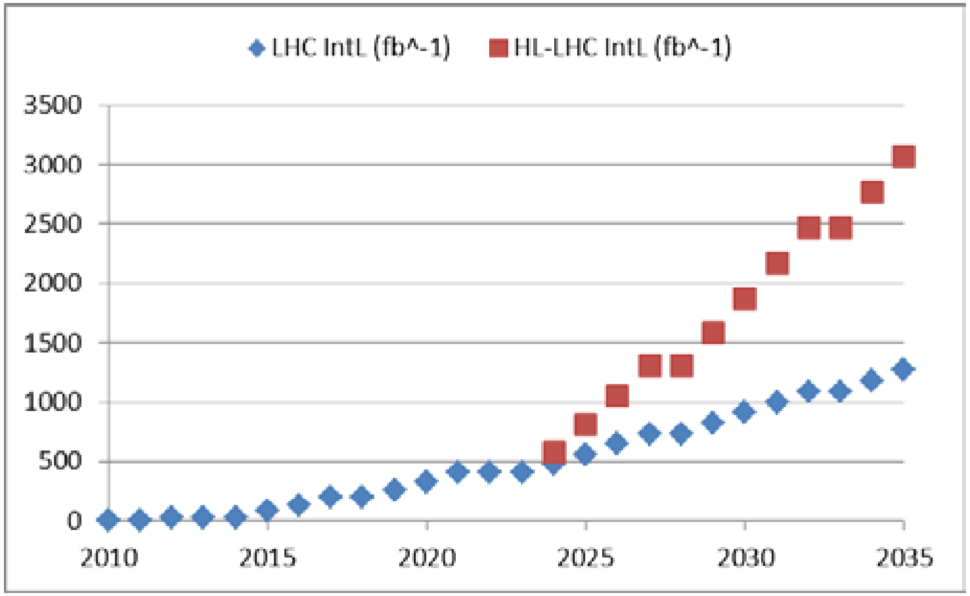
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_3b_2_2_2_with_nc_probes | PM Status B1 ENABLED | PM Status B2 ENABLED



Luminosity cycle for HL-LHC (with 'levelling', optimized for the experiments and integrated luminosity)

High Luminosity LHC



Projected integrated luminosity